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ABSTRACT

A training program was devised to develop automaticity of one subcomponent of reading--locating and disembedding multiletter units within words. The system involved the use of a training task that was implemented in a microcomputer-based game that required students to detect whether a target unit was presented within words that were shown in rapid succession. The purpose of the task was to increase student monitoring rates without increasing the number of errors made. Subjects participating in the training program were four high school students termed poor readers. Performance records indicate that the training program was successful. Substantial improvements were evident in both student learning rates and performance levels. Maintenance tests designed to measure the stability of the gains in speed conducted regularly after the training had ended yielded positive results. In addition, the students completed a battery of tasks (perceptual unit detection, pseudoword pronunciation, and span of apprehension) to gauge the transfer of training effects to other reading components. These test results showed that the training program enabled students to increase their efficiency in detecting units over a range of conditions. Transfer effects were also found in the pseudoword pronunciation task and on the span of apprehension task. (Materials used in the program are appended.) (FL)

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PERCEPTUAL UNITS TRAINING
FOR IMPROVING WORD ANALYSIS SKILLS

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Technical Report

March, 1982

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video screen. The goal of the game is for the student to get faster at monitoring for units without making too many errors.

Four students from a local high school were trained. They represented two groups of poor readers as measured on the Nelson-Denny Reading Test.

Performance records of students' progress on the task itself indicate that training was successful. Substantial improvements were evident in both learning rates and performance levels. Maintenance tests for assessing the stability of gains in speed on units after training on them had been terminated were run on a regular basis and the trainees were consistently successful on them. In addition, a battery of three criterion tasks (perceptual unit detection, pseudoword pronunciation, and span of apprehension) enabled us to assess the degree of transfer of training to a set of control units and to other reading components. Training had the effect of increasing students' efficiency in detecting units over the range of conditions represented and this effect generalized to units which had not been explicitly trained. Transfer effects were also observed in the pseudoword pronunciation task, with performance gains interpreted as being due to an increase in the quantity and accuracy of orthographic information that is being encoded rather than to an increase in decoding efficiency brought about by the availability of the acquired perceptual units. On the span of apprehension task (a measure of context utilization) training generally had the effect of reducing the effort involved in word recognition.

ERRATUM SHEET

The following corrections should be noted for Harvard Graduate School of Education Report No. 0001, entitled "Perceptual Units Training for Improving Word Analysis Skills:"

Page 50a, Figure 21 -- The caption should read, "Mario's performance (29th percentile) on the pseudoword decoding task."

Page 50b, Figure 22 -- The caption should read, "Tracy's performance (9th percentile) on the pseudoword decoding task.

The following Figures 23, 24, and 25 replace the original figures found on pages 51a, 51b, and 51c, respectively.

Span of Apprehension Task

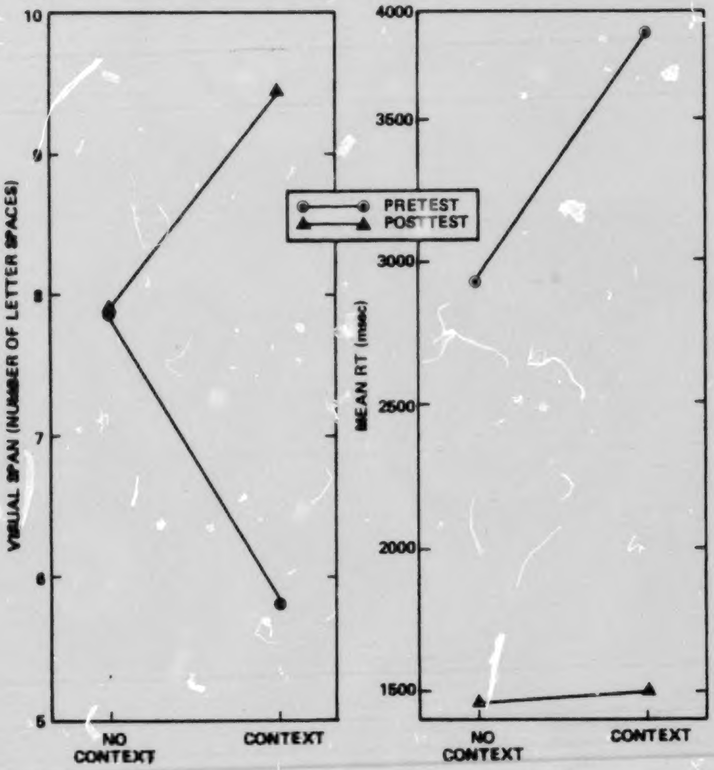

Figure 23. Jim's performance (10th percentile.

Span of Apprehension Task

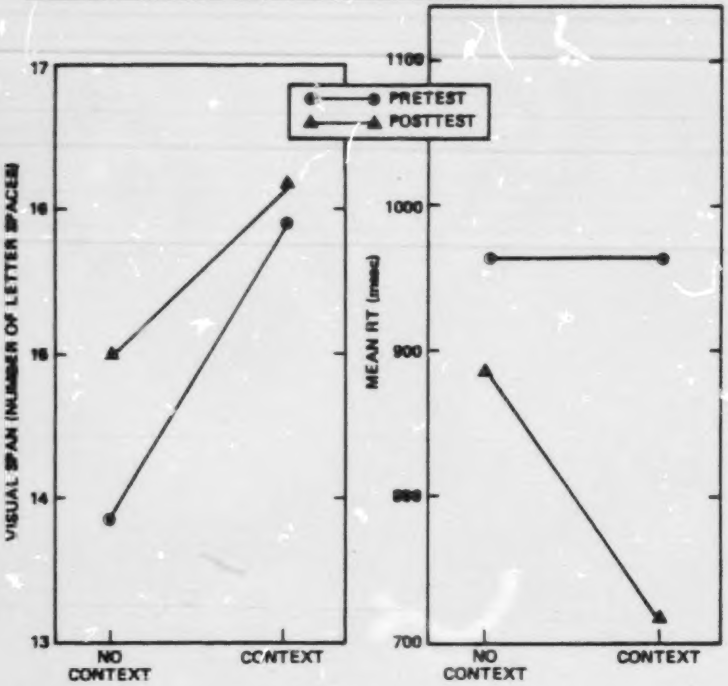

Figure 24. Mario's performance (29th percentile).

Span of Apprehension Task

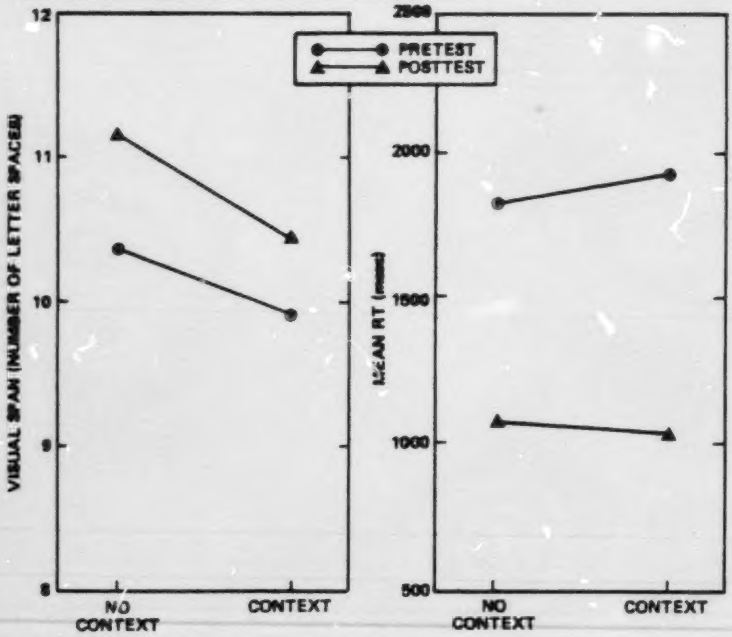

Figure 25. Tracy's performance (9th percentile.

Perceptual Units Training

for Improving Word Analysis Skills

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Abstract

This report provides a detailed account of a training system designed to develop automaticity of one subcomponent of reading, namely, locating and disembedding multiletter units within words. The training task, implemented in a microcomputer-based game, called SPEED, is one in which students are required to detect whether or not a target multiletter unit is presented within words which are presented in rapid succession on the video screen. The goal of the game is for the student to get faster at monitoring for units without making too many errors.

Four students from a local high school were trained. They represented two groups of poor readers as measured on the Nelson-Denny Reading Test.

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PERCEPTUAL UNITS TRAINING FOR IMPROVING WORD ANALYSIS SKILLS

Introduction

The work reported here is part of a larger ongoing effort to test a componential theory of reading (Frederiksen 1981; Weaver, 1980). Our goal in the series of investigations has been to improve the reading skills of young adults, especially those considered to be poorly skilled. We develop measures of components of reading in order to identify in poor readers those components that are deficient. Deficient components become the focus of short-term training programs (four to six weeks) that are designed to be component specific. On completion of training we use our measurement instruments to determine how and to what extent training at one level or in one skill domain generalizes to other components of reading. In this report we provide a detailed account of a training system designed to develop automaticity of one subcomponent of the word analysis component of reading, namely, locating and disembedding multiletter units within words. Features of the training both derive from that theory and inform it.

Our purposes in conducting the training study included:

1. Establishing that rapidly locating and disembedding multiletter units in words is a trainable subcomponent of reading. (We have already established that this skill does distinguish good from poor readers.)

2. Specifying and documenting the procedures and instructional environment appropriate for training perception of multiletter units;

3. Determining the general feasibility of short-term, microcomputer-based instruction for improving reading efficiency;

4. Evaluating the transfer of training in one skill component to reading performances that implicitly invoke that component, but that do not explicitly require the component for successful performance; and

5. Developing general specifications for an instructional methodology that is motivated by a componential theory of reading.

Before we present the background, procedures and findings of Perceptual Units Training, we offer a brief description of the componential theory of reading from which the training system is derived, as it was presented by Frederiksen (1981).

General Theoretical Framework

A componential theory of reading (or of any other complex performance) attempts to identify a set of functionally defined information processing systems or components which, in interaction with one another, accomplish the more complex performance--in this case, reading with comprehension. Component processes are defined by the types of data structures on which they operate (the domain or situation in which they operate), and by the specific transformations of those data structures that result (the function or action performed). Components can be thought of as corresponding to the production systems of Artificial Intelligence, which consist of situation-action pairs (Winston, 1979, p. 144). Productions (and components) are applied when their triggering situations occur. Their actions alter the internal data structures and therefore set the stage for still other productions. Productions--and components--are, in effect, always available for use, and are automatically applied whenever their defining input data structures make an appearance.

An advantage of production system theories is that no executive control processes need be postulated. Components will be applied in sequences that are determined by their pattern of interaction, as it is determined by their joint effects on a common internal data base. Thus, the controls over component operations reside in the specification of the situations in which they are applied. For example, in the theory of reading, a decoding process is postulated that has as input an orthographic array consisting of encoded letters or multiletter units. This process applies grapheme-phoneme correspondence rules and results in a pronunciation for the input array. The process cannot operate until its input situation occurs--namely, letters and/or multiletter units have been encoded. There is thus an automatic sequencing of processes for encoding orthographic units and decoding. However, encoding of multiletter units and encoding individual graphemes both require as input a set of visual features distributed spatially. These two components are, therefore, not sequentially organized.

In a componential theory, readers may be thought of as differing in the degree to which productions, or components, have become automated (cf. Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). Automatic processes can operate concurrently with other components, without degrading their efficiency of operation. In contrast, controlled (nonautomatic) processes make demands on general, shared processing resources; when they must operate concurrently with other processes, performance is degraded. A skilled reader possesses many, highly automated components, while a less skilled reader has a smaller number of such components, and those may vary considerably within the population of poorly skilled, young adult readers. Thus, while readers may be reliably classified along a single dimension of "general reading ability," the actual sources of low tested ability may vary considerably from reader to reader.

Overview of Components

In Figure 1 we have represented and described three major processing levels in reading. The reader has available to apply to information obtained during reading (1) a set of word analysis processes, (2) a discourse model generated by discourse analysis processes and (3) an ability to combine information from word and discourse sources by what we term the integrative processes. As indicated in the figure, we suggest a set of component processes that constitute each category.

Word analysis processes. Word analysis includes processing components involved in the perception of single-letter and multiletter orthographic units, the translation of orthographic information into a phonological representation, the assignment of appropriate speech patterns to such translated units (e.g., stress, pitch, contour), and the identification of lexical categories (which vary in the characteristic depth of processing required for retrieval). Note that the defining characteristics of these word analysis processes is that they are all limited to processing information available within a single word.

Discourse analysis processes. Discourse analysis processes are used for analyzing lexical and structural information at the text level (rather than at the word level) for the purpose of constructing a text model that represents the reader's understanding. These component processes include retrieving and integrating word meanings, constructing a propositional base (including analysis of noun groups and establishing case relations), analyzing cohesive relations among sentences or propositions, resolving problems of reference (anaphora and cataphora), constructing inferential elaboration of the text structure, and relating the text structure to prior knowledge of the subject matter and genre.

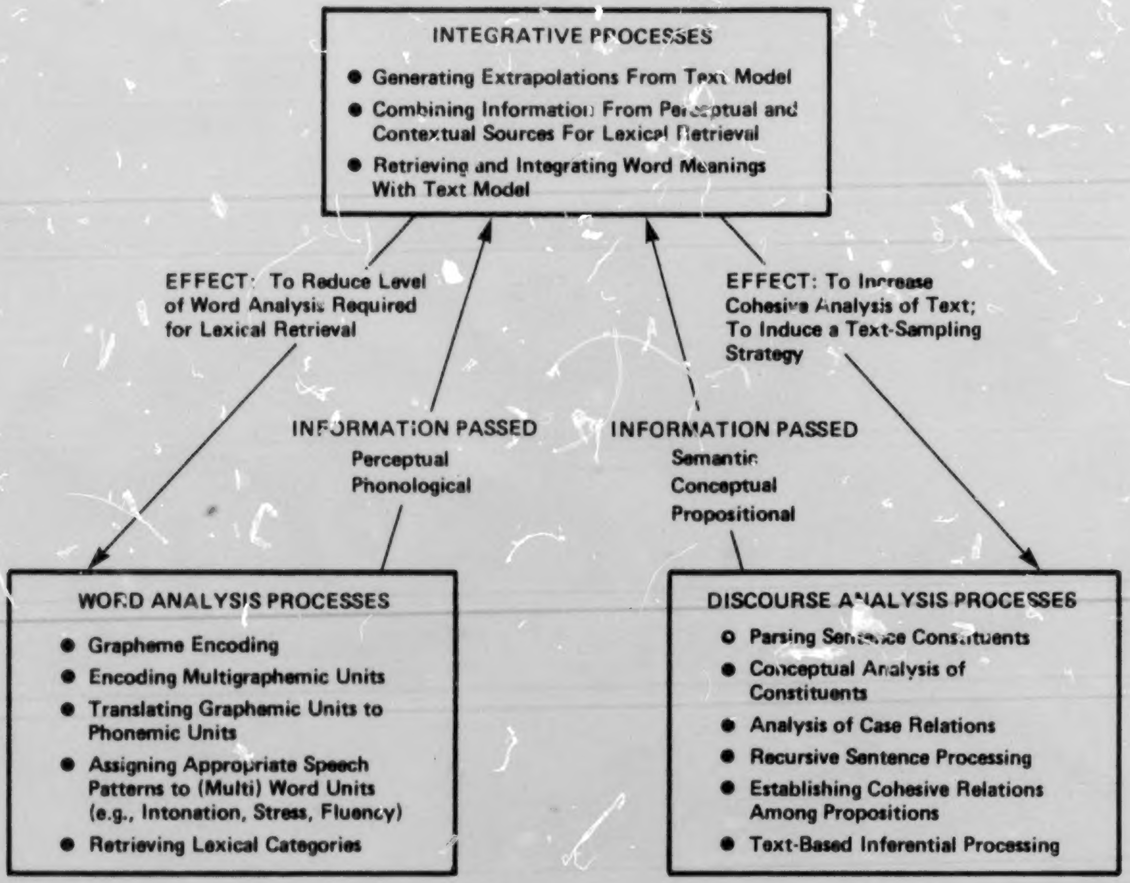

INTEGRATIVE PROCESSES
Generating Extrapolations From Text Model
Combining Information From Perceptual and Contextual Sources For Lexical Retrieval
Retrieving and Integrating Word Meanings With Text Model
EFFECT: To Reduce Level of Word Analysis Required for Lexical Retrieval
EFFECT: To Increase Cohesive Analysis of Text; To Induce a Text-Sampling Strategy
INFORMATION PASSED
Perceptual
Phonological
INFORMATION PASSED
Semantic
Conceptual
Propositional
WORD ANALYSIS PROCESSES
Grapheme Encoding
Encoding Multigraphemic Units
Translating Graphemic Units to Phonemic Units
Assigning Appropriate Speech Patterns to (Multi) Word Units (e.g., Intonation, Stress, Fluency)
Retrieving Lexical Categories
DISCOURSE ANALYSIS PROCESSES
Parsing Sentence Constituents
Conceptual Analysis of Constituents
Analysis of Case Relations
Recursive Sentence Processing
Establishing Cohesive Relations Among Propositions
Text-Based Inferential Processing

Figure 1. Categories of reading processes and the nature of their interactions.

Integrative processes. At the moment of visual fixation, the reader has available (a) perceptual, phonological, and structural information about lexical items included in the fixation, and (b) semantic, conceptual, and propositional knowledge resulting from the analysis of prior discourse. Integrative processes permit the reader to combine information from these multiple sources, yielding a set of lexical identifications for the fixated items. The components of the integrative processes are directly related to the sources of available information. They include the extrapolation of the discourse model in terms of generating semantic-syntactic forms which can be expected to occur in the text to follow, and the utilization of this information so as to more readily make lexical identifications. The generative process may, in a skilled reader, resemble the spread of activation postulated by Collins and Loftus (1975). The integrative utilization of perceptual and semantic information requires a mechanism such as the logogen, postulated by Morton (1969).

Component Interactions

Within or between these processing areas, components can interact by virtue of their effects on the common internal data base and their usage of shared processing resources. Together, these mechanisms provide for a number of functionally determined types of component interaction.

Data-linked components. Components can interact by virtue of their operating on a common memory store. For example, two components may require common input information structure, but otherwise operate independently. Such components are linked through correlated input data. Other components may in their operation construct input data structures that are needed by other components. Their operation will thus determine the usage of the later-occurring processes, so that together the components

Table 1

Types of Component Interactions

I. Functionally Determined Interaction
    A. Data-Linked Components
        1. Correlated Input Data
        2. Cascaded Processes
        3. Dependent Processes
        4. Mutually Facilitory Processes
    B. Process-Linked Components
        1. Shared Subprocesses
        2. Shared Control Processes
    C. Resource-Linked Components
        1. Due to general processing capacity
        2. Shared memory access/retrieval channels
        3. Limited capacity working memory

II. Nonfunctional Sources of Process Intercorrelation
    A. Etiologically-Linked Components
        1. Reflecting a learning hierarchy
        2. Reflecting effectiveness of learning environments
    B. Reflecting general, biologically determined ability

form a processing hierarchy. If two processes run concurrently, but the second process improves in efficiency and quality of output as the first process runs further to completion, the processes are called cascaded processes (cf. McClelland, 1978). If the operation of the second process depends upon data structures created by the first process running to completion (or to some fixed point), the processes are dependent processes. Finally, concurrent processes may both operate on a common data store, and if attendant changes in the data store caused by one process facilitate (or otherwise alter) the operation of the other process, then the components are mutually facilitative.

Process-linked components. Components can also interact by virtue of their mutual dependence on the operation of other component processes; such components are termed process-linked components. For example, two components might require a common or shared subprocess for their execution. Alternatively, two components might be invoked by a single shared control process. (This latter case is formally a special case of processes linked through correlated input data; here, of course, the emphasis is on the third component, which creates the required data structures.)

Resource-linked components. A third form of functional interaction among components occurs when two or more components must compete for common or shared processing resources. Such components are called resource-linked components. Shared resources might include use of a limited-capacity processor, shared memory access/retrieval channels, or limited capacity working memory (cf. Perfetti & Lesgold, 1977; 1979). When two processes are in competition for resources, increases in the automaticity of one process will free resources for the second process.

In our previous research (Frederiksen, 1981), we tested hypotheses concerning interactions among components in the word analysis, discourse analysis, and integrative domains, using the analysis of covariance structures (ACOVS) approach of Jöreskog (1970), and Jöreskog and Sörbom (1977). First, measurement models were validated for each domain, whereby individual differences in performance on componentially-specific tasks were resolved by establishing task loadings on components. Alternative measurement models were also tested, for the purpose of establishing the validity of each hypothesized component. Table 2 gives a summary of components identified in each of the three domains.

Second, adopting the validated measurement models for each processing domain, we tested hypotheses concerning interactions among components. This was accomplished by building a set of structural equations describing the hypothesized interactions among reading components, demonstrating identifiability of parameters, and testing the model by use of the ACOVS procedure. A chi-square test then allowed us to compare alternative structural models against the "null" case where only the measurement model was specified and all components were free to intercorrelate with one another. Results of this procedure applied to our measures of word analysis, are shown in Figure 2. Components I, II, III, and IV represent respectively, the word analysis processes of Letter Recognition, Perceiving Multiletter Units. Decoding, and Efficient Word Recognition. Components I and II both contribute to efficient, automatic decoding, but are themselves independent. Furthermore, their effect on word recognition is indirect, through their effect on decoding. Efficient word recognition is not associated with perceptual skills I and II, but is strongly related to efficient decoding. However, component-specific individual differences are the most important determiners of decoding and word recognition efficiency. Taken together, these observations suggest that

Table 2

Components Identified in ACOVS for Reading Measures

Word Analysis

I. Letter Encoding Efficiency

II. Perceiving Multiletter Units

III. Decoding or Phonological Translation

IV. Efficiency in Word Recognition

Context Utilization

V. Speed Set in Applying Context to Identify a Highly Predictable Target

VI. Extrapolating a Discourse Representation to Upcoming Text (Activation of Semantically Related Items within LTM)

Discourse Analysis

VII. Preference for Topicalized Antecedent as Referent

VIII. Semantic Integration of Antecedents with Discourse Representation in Working Memory

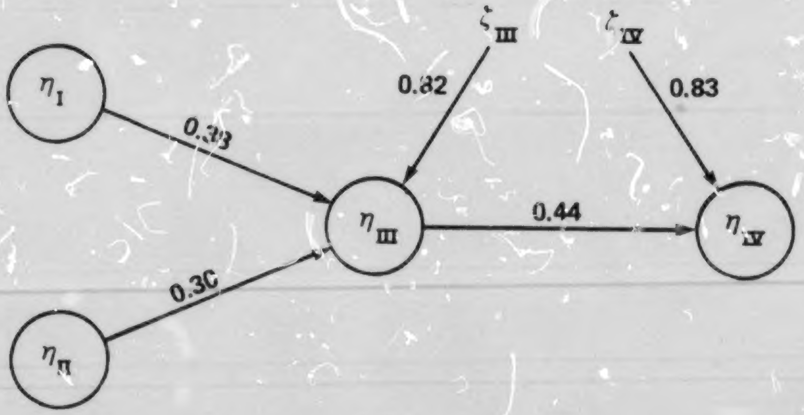

ζ_{III}
ζ_{IV}
η_{I}
0.33
0.82
0.83
η_{III}
0.44
η_{IV}
0.30
η_{II}

Figure 2. Structural model for interactions among Word Analysis Components: I (letter recognition), II (multiletter unit perception), III (decoding), and IV (efficient word recognition).

automaticity training in the perceptual skills (particularly II), when integrated with training in efficient decoding, can have a substantial impact on efficiency in word recognition.

But what are the relations of these reading components to components of discourse processing, or to the abilities involved in utilizing contextual information to guide lexical retrieval? The pattern of process interaction for the first set of "high level" components--context utilization components--is displayed in Figure 3. Component VI, Generating Extrapolations from a Discourse Representation, and V, Speed Set in Employing Highly Predictive Context, are two identifiable aspects of context utilization. The generative component, VI, is related directly to word recognition efficiency (IV), and indirectly to the other word analysis components, through their effects on IV. Speed in utilizing predictive context (V) is negatively related to the generative component (VI), and represents a strategy that is most applicable when the generative component yields a small (unitary) set of constrained alternatives. The correlations of the strategic component (V) to the other components are all attributable to its relation to the more basic generative component.

The relationships of Discourse processing components to lower-level components are shown in Figure 4. Component VIII has been interpreted as representing efficiency in integrating semantic information associated with an antecedent lexical item with the discourse representation currently formulated by the reader. Semantic integration is not significantly associated with word recognition (IV), but it is strongly associated with Decoding efficiency (III), with r = .87 and a regression coefficient of .91. Thus, there is a direct effect of automatic decoding on this discourse processing component. We interpret this direct influence as an example of process interaction due to competition for a limited resource (Perfetti & Lesgold, 1977).

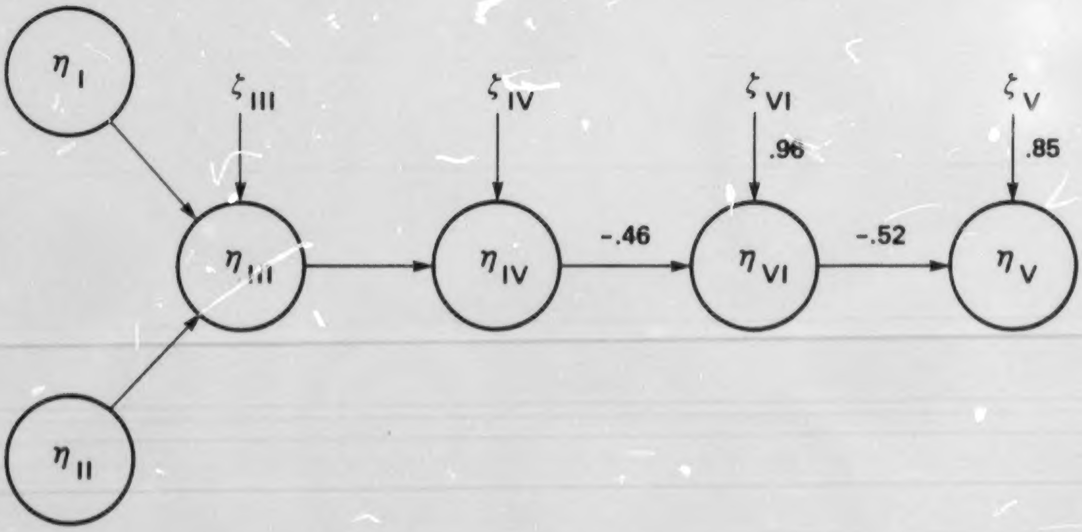

η_I
η_{II}
ζ_{III}
η_{III}
ζ_{IV}
η_{IV}
-.46
ζ_{VI}
.96
η_{VI}
-.52
ζ_V
.85
η_V

Figure 3. Structural model for interactions among Context Utilization Components: V (speed set in employing highly predictive context), and VI (generating extrapolations from a discourse representation).

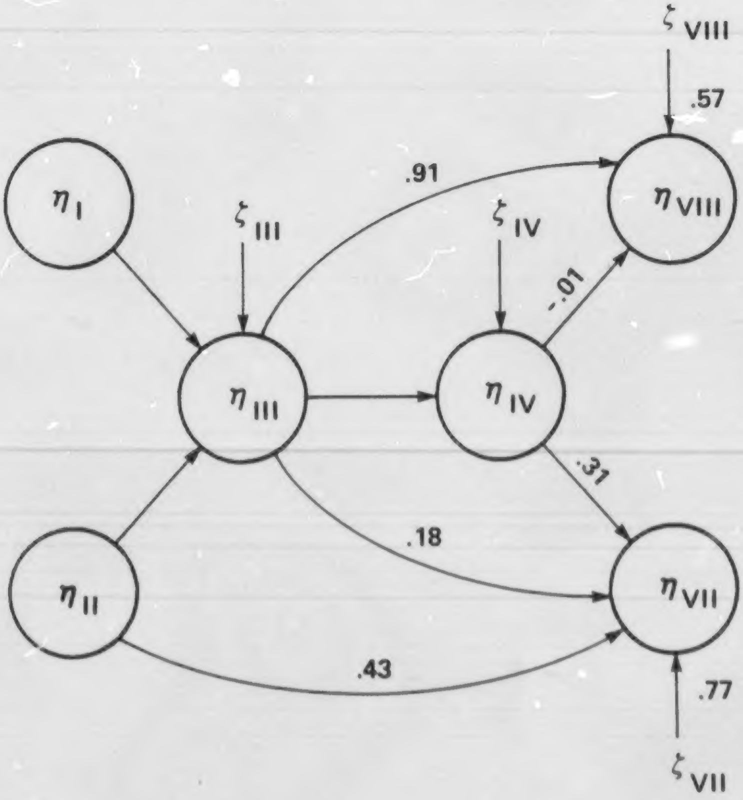

ζ_{VIII}
.57
.91
η_{I}
ζ_{III}
ζ_{IV}
η_{VIII}
-.01
η_{III}
η_{IV}
.31
.18
η_{II}
η_{VII}
.43
.77
ζ_{VII}

Figure 4. Structural model for interactions among Discourse Processing Components to Lower Level Components: VII (preference for a topicalized antecedent as a referent), and VIII (efficiency in integrating semantic information associated with an antecedent lexical item with the discourse representation).

Efficient decoding has an important, direct influence on discourse processing. And we are led to entertain the hypothesis that training for automatic decoding may have an impact on efficiency of discourse processing. The remaining discourse processing component we have identified (VII), preference for a topicalized antecedent as a referent, is reflective of a dependence on the part of the reader on the topical status of antecedents in effecting retrieval from memory. VII is associated with three word analysis components, suggesting again that automaticity of low-level processes contributes to efficiency in processing at the text level presumably through lessened demands on the processing resource.

Relation of Components to Reading Ability

In a validation study (Frederiksen, 1981), we have explored the relation of reading components to cognitive ability tests, and to general measures of reading ability. Correlations of the eight reading components with four criterion measures of reading ability are given in Table 3. Of the reading components we have studied, components of word analysis, particularly decoding automaticity and word recognition efficiency, show the strongest relations to criterion measures of reading ability. Correlations of decoding efficiency with Reading Time (.70), Vocabulary (-.62), and Comprehension (-.68) were particularly high. Corresponding correlations for word recognition efficiency were .50, -.35, and -.51. We believe that the explanation for these correlations is the disruptive effect of effortful decoding on ongoing processing of discourse propositional context. Good and poor readers alike encounter words in text that they do not recognize automatically. Component IV, Word Recognition Efficiency, indexes the amount of decoding effort involved in recognizing and pronouncing less familiar words. The correlations with reading ability measures reported above indicate that the poorer readers are likely to have a smaller

Table 3

Validity Coefficients*

		Criterion Measure			
	Component	Reading Time for Context	Nelson-Denny Speed	Nelson-Denny Vocabulary	Nelson-Denny Comprehension
I.	Letter Encoding	.17	-.18	-.31	-.20
II.	Perceiving Multiletter Units	.20	-.28	-.30	-.29
III.	Decoding	.70	-.48	-.62	-.68
IV.	Word Recognition Efficiency	.50	-.17	-.35	-.51
V.	Speed in Applying Context	.42	-.03	.00	-.21
VI.	Extrapolating a Discourse Representation	-.51	.37	.47	.59
VII.	Influence of Topicality of Reference	.23	-.17	-.23	-.34
VIII.	Semantic Integration of Antecedents	.41	-.11	.08	.02
	Multi R	.74	.63	.73	.76
	F (7, 38)	6.48	3.63	6.08	7.50
	Prob.	.000	.000	.000	.000

*Correlations of .25 or greater are underscored.

vocabulary of words they can recognize automatically, and that consequently, on the average more decoding effort will be required of them in reading. Correlations with Decoding Efficiency indicate that the effort required when a word cannot be automatically recognized will be greater for lower ability readers. The fact that correlations for Decoding Efficiency are the highest of all validity coefficients in Table 3 indicates that the severity of the disruption when encountering and decoding an unfamiliar word may be more serious than the frequency of such disruptions. A highly skilled reader can apply automatic decoding processes in such cases, which will not interfere with ongoing processing of discourse propositional structure. It is for this reason that we have focused on the development of automatic word analysis as the first objective of our training program.

Focus of Training

On the basis of research we have completed, we can offer a tentative profile of the word analysis processing of a highly skilled reader and contrast it with that of a less skilled reader. The skilled reader has a sizeable vocabulary of sight words as well as effective and automatic procedures for decoding unfamiliar words. Efficient decoding for such a reader appears to begin with the automatic recognition of perceptual units larger than the single letter. These units form the basis for subsequent decoding/lexical access. Poor readers, on the other hand, appear to be in triple jeopardy. First, their sight vocabularies are smaller, necessitating active decoding on a larger number of occasions. Second, the decoding process is effortful and disruptive of other concurrent processing tasks in sentence understanding. Third, their decoding effort must begin with individual letters and only the most common multiletter units. We have speculated that decoding from individual letters requires more complex rules (cf. Venezky, 1970) than would decoding from a properly chosen and probably rather large "vocabulary" of multiletter units.

We have taken a two-tiered approach to the task of validating this profile of expertise in word recognition. First, we have attempted through a computer simulation (PARSYL) to explicitly demonstrate how a careful choice of a perceptual unit vocabulary can allow accurate decoding using a highly simplified set of rules for translation. Second, we have verified experimentally that on the specific unit vocabulary developed for the simulation, there are differences between good and poor readers in "unit bandwidth"--the set of those perceptual units for which automatic detection operates.

Our training procedures are predicated on the results of these two investigations, the PARSYL simulation and the BANDWIDTH experiment (Frederiksen, et al., 1982). The PARSYL simulation enabled us to select for training a set of units that appear to have the greatest utility in correctly syllabifying words. The BANDWIDTH experiment established that there were differences among readers in the ability to rapidly detect those units in a situation in which perceptual processing was limited to a brief exposure. Contributing to the poor reader's difficulty in detecting units was a unit's position within a stimulus word. Such readers had particular difficulty when the units were embedded within words rather than occurring at the beginning or end. These findings determined our instructional objectives in the Perceptual Units Training System (PUTS). We sought (1) to develop a wide and specific unit vocabulary, and (2) to foster the ability to distribute perceptual/attentional resources over an entire visual array so as to rapidly effect recognition of embedded units. Both objectives address one of the most well-established sources of deficit in reading skill and one of the most difficult of those to remedy: the poor reader's tendency to attend only to the beginning and perhaps ending of a word that he cannot recognize on sight and then employ a guessing strategy for the rest (Harris & Sipay, 1975). Standard reading practice has focused on the first objective--the development of a specific vocabulary of spelling patterns/phonograms which then serves as a basis by which the learner can distinguish among words having common beginning and ending letters. Our instructional focus, in addition to building a specific unit vocabulary, includes an effort to modify the poor reader's distribution of attention in word perception.

Method

Introduction to the Instructional Design

In the subsequent sections of this report, we present in detail the features, procedures, and outcomes of Perceptual Units Training. As the design for instruction is an outgrowth of our componential theory of reading, there is not a separate theory of instruction. Indeed, the componential theory of reading with its explicit model for process interaction, coupled with principles drawn from theories of learning, directly suggest instructional plans and procedures. In this way, effects of instruction on component reading processes are themselves a test of the reading model.

Such an approach to instructional design--based directly on a theory of reading, but not forming a separate theory of instruction--is perhaps best captured by an architectural analogy. We refer to our current work as an instructional architecture, and to our instructional plans as blueprints, serving much the same purpose that an architect's plans serve in the construction of a building. Our instructional blueprints are informed and constrained by our theory in much the same way as an architect draws up a set of building plans which are constrained by architectural theory and by specific purposes of the design including function, cost, durability, and so forth. The principal constraint associated with our theory of reading which carries over to the aim of instruction itself is automaticity or efficiency in performance, realized as a balance between speed and accuracy. Efficiency acts as a functional constraint on which successful performance depends. Similarly, principles from learning theory particularly regarding motivation and practice serve more or less as structural constraints to guide and inform instruction much as an architect is constrained by stress mechanics, building codes, and slope of the land in finalizing building design and construction. Our instructional blueprints, then, reflect the combined constraints of our model of reading, the aims of instruction, and theories of learning.

Deriving training goals and procedures from a componential model of reading suggests certain instructional features which when compared to "party line" reading instruction appear somewhat unorthodox:

1. Training on the skill is carried out in strict isolation rather than being embedded in a task that requires other skills as well for its execution;

2. We do not instruct directly because for perceptual unit detection we cannot specify the nature of the behavior or behaviors that result in a change from less to more skilled performance. We therefore demand that the training environment simulate, though not necessarily duplicate, the actual environment in which the target skill is performed so that "correct" performance can be rewarded;

3. Training is designed to tolerate and promote a certain amount of error in the service of developing automaticity.

Some elaboration on each of these points follows.

In more traditional reading instructional systems, isolated skills practice is usually regarded as ecologically invalid. Instead, practicing the target skill in the context of actual reading is favored. We argue that such "integrated" practice is inefficient and often ineffectual since the student must spread attention over a number of skills and may not even know which skill is to be perfected. This is especially pertinent for the poor reader whose resources are quickly depleted in carrying out complex reading tasks. Furthermore, in the effort to make training resemble "real reading," a certain amount of instructional control is sacrificed; you simply cannot be sure that the student is engaged in the proper activity instead of some compensatory behaviors whose outcomes match those of the targeted skill. Thus our training procedures are designed to focus on a single skill and provide practice on that skill until it is automatized. This is guaranteed by interlocking success on the training game with successful skill performance. That is to say, it is impossible to improve gamesmanship without improving skill in perceptual unit detection, and there is no compensatory skill which can be substituted into the game.

We know that poor readers are slower than good readers in locating and disembedding multiletter units in words (Frederiksen, 1978). We suspect that good readers are faster because they are more flexible in perceiving units and unit boundaries as these change from word to word. But we cannot be sure that this is so, anymore than we could be sure of the way such flexibility, if it did exist, were translated into perceptual processing. Thus we cannot direct the inefficient reader to do what the good reader does. But we can structure the task environment in such a way that the poor reader is constantly informed of his progress and reinforced for the proper skill behaviors. This sort of self-regulation resembles a biofeedback technique in that how an individual comes to improve is less important than establishing conditions in which proper change is evidenced and reinforced. In such a system, continuous feedback is required so that an individual may regulate his performance. In the case of Perceptual Units Training, the dual sources of feedback are speed and accuracy, and the student finds a way to get faster at monitoring for units without making too many errors.

As with the biofeedback technique, it is necessary for the individual to know the boundaries between good and poor performance so that processes can be regulated. For the hypertensive individual, a device signals higher-than-tolerable blood pressure. Such infractions are necessary so that the individual can come to "feel" the difference between too-high and not-too-high blood pressure. Similarly, our students must find the optimal interplay of speed and accuracy. It is all right to commit some errors if there is a marginal benefit in speed. Likewise, being somewhat slower is admissible if getting faster means committing too many errors. The features of our training game--SPEED--were designed to simulate the sort of speed-accuracy bind in which a good reader finds himself and seems able to parlay into optimally skillful performance.

The Training Task: SPEED

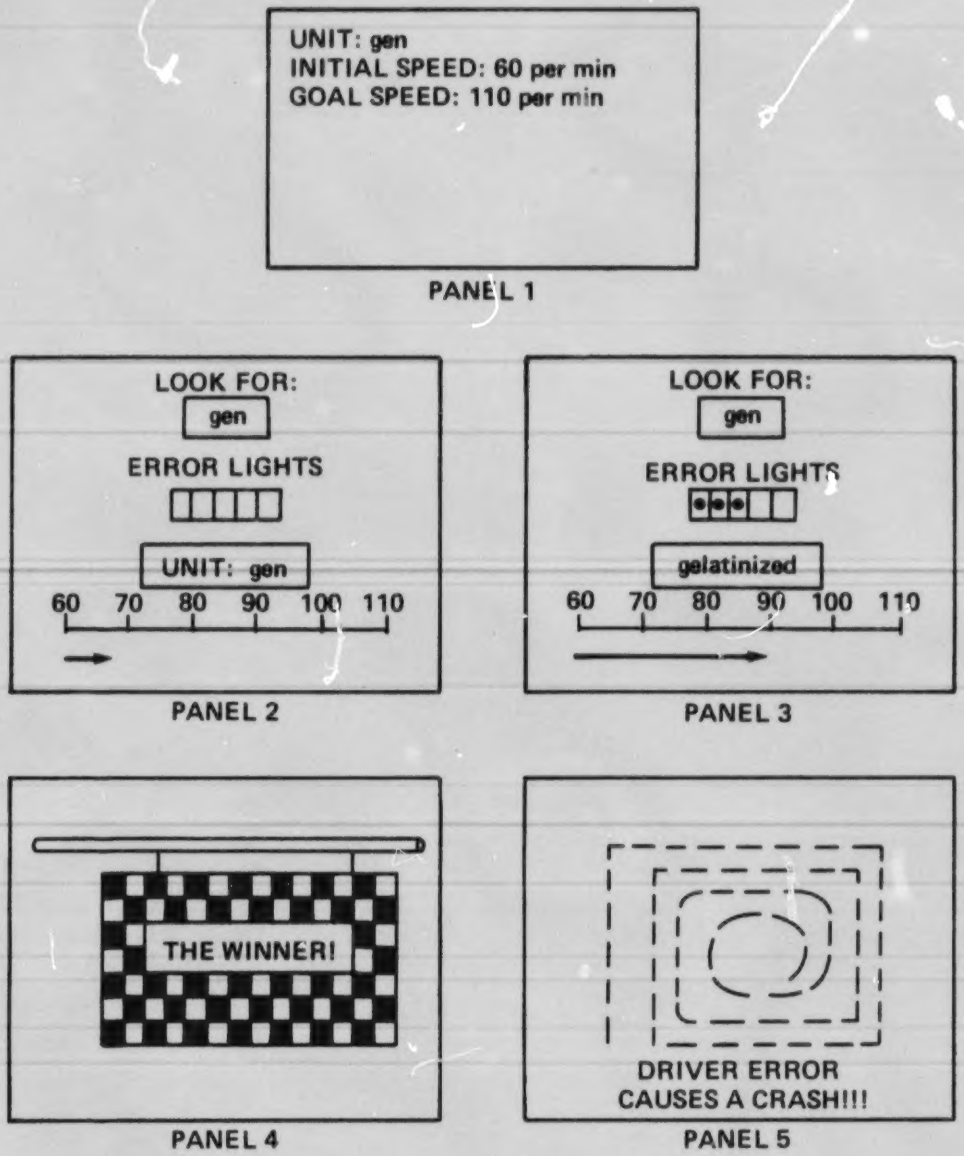
The training task, implemented in a microcomputer-based game called SPEED, is one in which the trainees are required to detect a target multiletter unit when it appears within stimulus words presented in rapid succession. On each training trial, a student is presented a target unit and then a series of stimulus words in which the unit is either present or absent. His task is to indicate for each word whether or not the target unit is present by pressing the appropriate response key. The positions of target units within words vary. Rapid detection of units thus requires the trainee to distribute his attention over the entire visual array.

In general, the goal of the game is for the student to accelerate his rate of unit detection without sacrificing accuracy. The rate at which the stimulus words are presented begins at an initial speed of, for example, 60 items per minute and, depending upon the trainee's performance, increases in the direction of a goal speed which is set at 50 units above the initial speed. Increases in speed are contingent upon correct detection of the target multiletter unit. In an effort to simulate actual reading processes, a few errors (registered as error lights) are tolerated, but at the expense of speed reductions. In this way, when the trainee begins to commit errors, he is forced to slow down until he can reestablish accuracy. This is in contrast to the good reader who knows to slow down when the reading task becomes more complex, hence more demanding of his attention. The trainee is thereby caught in speed-accuracy bind--faster is better, but not at the expense of accuracy. The intention underlying the design of SPEED, then, was to build features of the efficient reader into the game, presuming that with a large dose of carefully monitored and highly informative practice, poor readers would learn to do what seems to come naturally to good readers.

Display formats. Initially, the program identifies the unit to be trained, its initial speed, and its computed goal speed as shown in Panel 1 of Figure 5. Once the game begins, the display is that of Panel 2 and contains the following features:

1. the target unit is identified at the top with the heading:
   "Look for: gen;"

2. five error lights are located directly below the identified target unit;


UNIT: gen
INITIAL SPEED: 60 per min
GOAL SPEED: 110 per min
LOOK FOR:
gen
ERROR LIGHTS
UNIT: gen
60
70
80
90
100
110
LOOK FOR:
gen
ERROR LIGHTS
gelatinized
60
70
80
90
100
110
THE WINNER!
DRIVER ERROR
CAUSES A CRASH!!!

PANEL 1

PANEL 2

PANEL 3

PANEL 4

PANEL 5

Figure 5. Display formats in the game SPEED.

3. the target words appear in a window located in the center of the display; and,

4. a speedometer is positioned at the bottom.

When a student wins or loses the game, one of two special displays appears (Panels 4 and 5).

Events within a trial. The dynamics of the game are represented in Figure 6 in which changes in the rate of word presentation and in the error lights and speedometer are related to the student's responses on each stimulus word presented within a trial.

The speed of item presentation is set by varying the time each item remains displayed. A starting speed of 60 corresponds to an initial display time of t = 1000 msec. Trainees must respond within that interval. If the response is correct, two things happen: first, if there are any error lights currently on, one is turned off; second, the time t used for the next stimulus presentation is reduced by 32 msec (corresponding to an increment of 2 speed units on the speedometer). If this upwardly adjusted speed matches the set goal speed, the trainee wins the game and is shown the "WIN" display. In the event the goal speed has not been reached, the speedometer display is revised, and if items remain in the list, the next item is presented.

When the trainee's response to a new item is incorrect (or when he fails to respond in the allotted time), the speedometer and error lights undergo other adjustments. If five error lights are already on, the trainee "CRASHES." Otherwise, an additional error light is registered (Panel 3, Figure 5) and the time for the next item is increased by 32 msec, with the corresponding 2-unit decrement registered on the speedometer.

Whenever the program attempts to present the next list item,

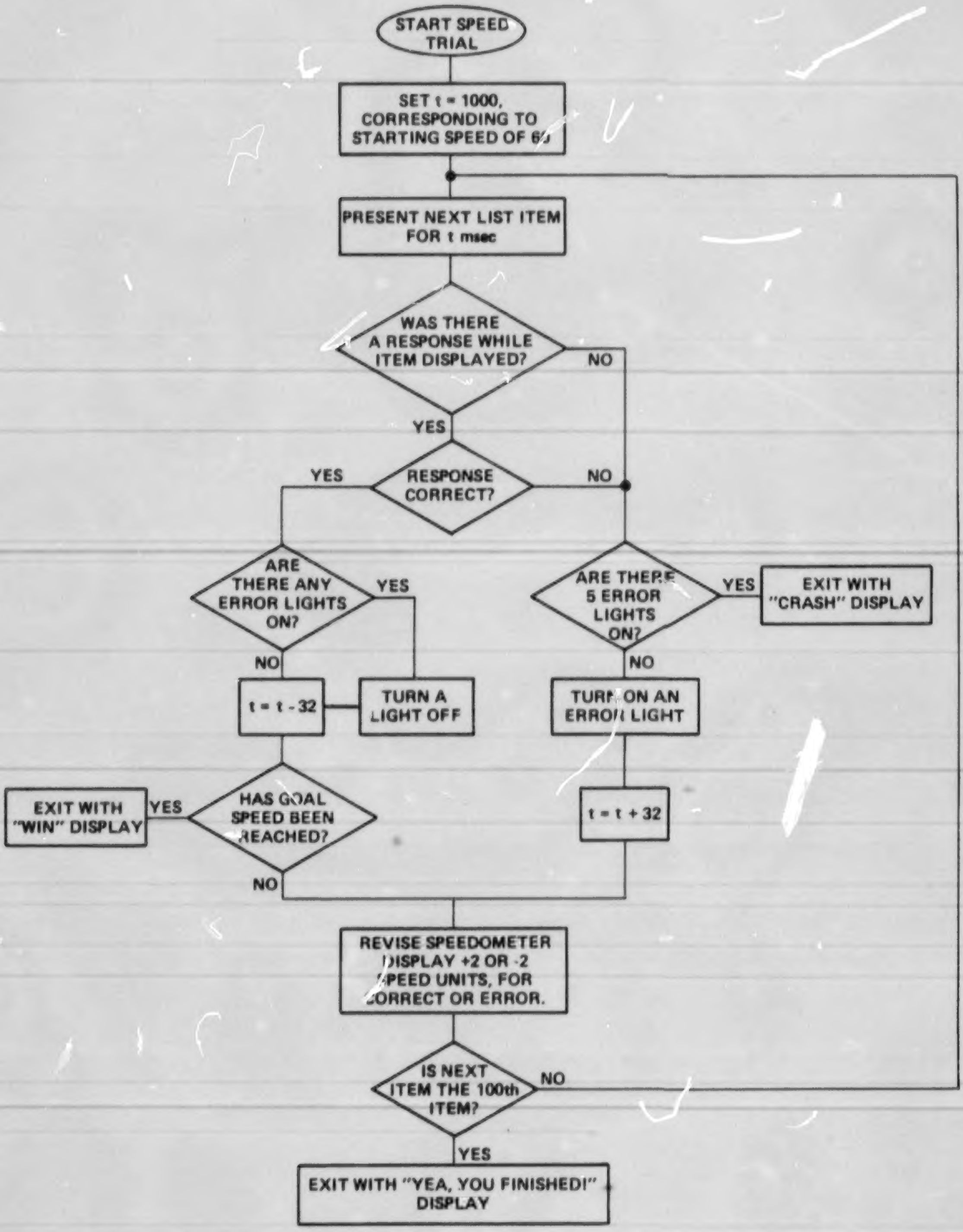

START SPEED TRIAL
SET t = 1000, CORRESPONDING TO STARTING SPEED OF 60
PRESENT NEXT LIST ITEM FOR t msec
WAS THERE A RESPONSE WHILE ITEM DISPLAYED?
NO
YES
RESPONSE CORRECT?
YES
NO
ARE THERE ANY ERROR LIGHTS ON?
YES
NO
t = t - 32
TURN A LIGHT OFF
ARE THERE 5 ERROR LIGHTS ON?
YES
EXIT WITH "CRASH" DISPLAY
NO
TURN ON AN ERROR LIGHT
t = t + 32
EXIT WITH "WIN" DISPLAY
YES
HAS GOAL SPEED BEEN REACHED?
NO
REVISE SPEEDOMETER DISPLAY +2 OR -2 SPEED UNITS, FOR CORRECT OR ERROR.
IS NEXT ITEM THE 100th ITEM?
NO
YES
EXIT WITH "YEA, YOU FINISHED!" DISPLAY

Figure 6. Flow chart representing the dynamics of the game SPEED.

it checks to see if the list has been exhausted. If it has, the message, "Yea, you finished!" appears in the stimulus window.

Completely error-free performance enables the trainee to reach the goal speed after seeing 25 list items. But success on the game does not demand error-free performance. Rather, the game is a benevolent taskmaster--during a trial, the trainee can erase errors. However, continual alternation between errors and correct responses will permit no progress in speed, although it will keep the error lights low.. Therefore, in order to progress in speed, the frequency of the errors must be kept low.

Subsequent trials. Initial and goal speeds on the second and subsequent trials on a unit are governed by the trainee's past levels of performance on the unit. At the beginning of a trial, the program accesses the final performance level on the previous trial and sets a new initial speed at 30 units below that. For example, if a trainee reached a final speed of 110, the new initial speed would be set at 80 and the corresponding goal speed set at 130. Therefore, the game becomes more demanding with each trial, but not so demanding that it is beyond the student's ability at that particular time.

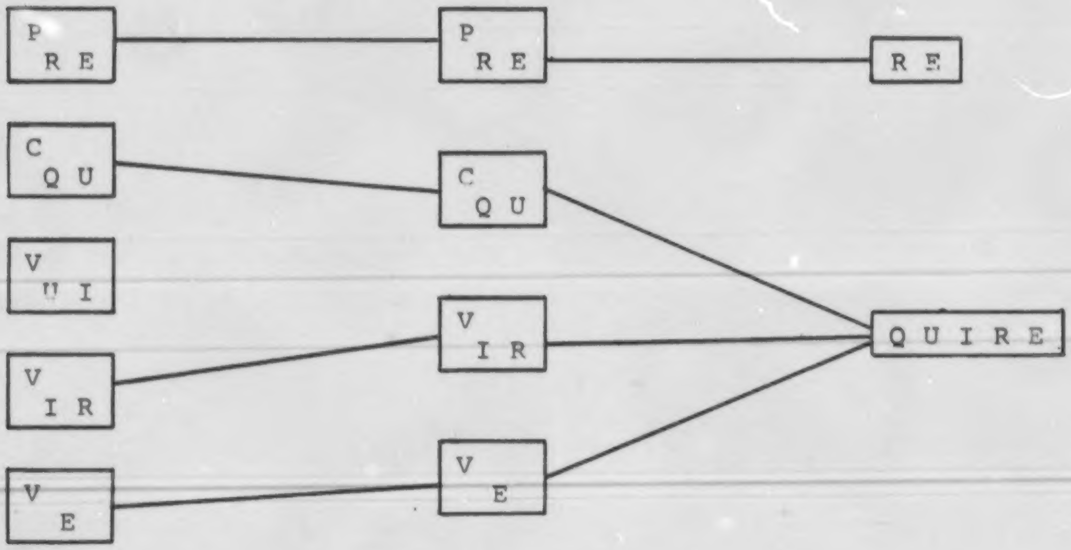
Materials

Multiletter units selection. We have designed and carried out a computer simulation which parses words into multiletter perceptual units and then applies a set of heuristics for joining the perceptual units into pronounceable syllable or vocalic units. The primary purpose of the simulation was to demonstrate that a simplified decoding process could be realized if a proper set of multiletter units constituted the input. PARSYL also enabled us through an iterative process to converge on the smallest unit vocabulary that would at the same time permit accurate and efficient decoding. Following the final selection of units, an experiment (BANDWIDTH) was conducted to collect performance data on readers of varying abilities to order and cluster the units with respect to their difficulty.

The PARSYL program, illustrated in Figure 7, has three components: unit identification, heuristic rules for simplifying unit descriptions, and syllabication rules. Unit identification is parallel and resembles a pandemonium or logogen model. All units are identified, even those that overlap with other units or are subsumed by larger units. For this reason, a set of parsing rules were developed which, to our best guess, duplicate some of the features of the human perceptual system. These rules are presented in Table 4. As the table indicates, large units subsume smaller units within them, and other things being equal, left-hand units are constructed ahead of right-hand units. The resulting perceptual parse contains a sequence of nonoverlapping units. These units, furthermore, are classified either as having a vocalic element or as purely consonant. In addition, the system includes prefix and suffix units. The PARSYL simulation only attempts to represent one aspect of decoding, namely, syllabication. Table 5 contains the simplified set of syllabication rules employed in the program. Tables 6-8 provide examples of sample output.

Application of the PARSYL program to analyze several test vocabularies enabled us to converge on a final optimal unit file. The first run of the PARSYL program, using a file of 499 units, yielded a 43% accuracy rate on a 1767 word sample. Revisions in the unit file were then made, in a series of iterations, in order to select a unit list that was maximally useful for syllabication and at the same time minimal in size. A final run of PARSYL yielded a 50% accuracy rate of the 1767 word sample from the Bolt Beranek and Newman System-D dictionary, compared to 43% previously. Sixty-one percent of the syllables created by the program were correct. For the Navy vocabulary, 58% of the words

Parsyl Simulation

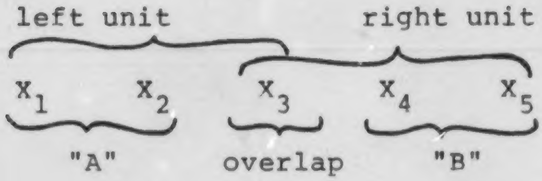

P
R E
C
Q U
V
U I
V
I R
V
E
P
R E
C
Q U
V
I R
V
E
R E
Q U I R E

Parallel Unit Detectors	Perceptual Parsing	Syllabication
	Heuristic Principles:	Simplification of Rules of Spoehr & Smith
Pandamonium	Large subsume small units	
	Left subsume right	

Figure 7. Components of the PARSYL program.

Table 4

Parsing Rules



If length of left unit equals length of right unit:

If A = U and B $\neq$ U, then

parse as $(x_1x_2)(x_3x_4x_5)$

If B = U and A $\neq$ U, then

parse as $(x_1x_2x_3)(x_4x_5)$

If A = U and B = U, then

parse as $(x_1x_2x_3)(x_4x_5)$

If A $\neq$ U and B $\neq$ U, then

parse as $(x_1x_2x_3)(x_4)(x_5)$

If length of one unit greater than length of other unit:

If length(left) > length(right), then

parse as $\left(\begin{smallmatrix}\text{left}\\\text{unit}\end{smallmatrix}\right)$ + remaining pieces

If length(right) > length(left), then

parse as remaining pieces + $\left(\begin{smallmatrix}\text{right}\\\text{unit}\end{smallmatrix}\right)$

Table 5

Syllabication Rules

A. Initial/Terminal Strings of C's

1. C C V . . . → (CCV..) ...
2. . . . V C C → ... (..VCC)

B. Medial C-Strings

1. . . . V C V . . . → (..V) (CV..)
2. . . . V C C V . . . → (..VC) (CV..)
3. . . . V C C C V . . . → (..VC) (CCV..)

C. Terminal-E Rule

. . . V E → ...(..VE)

D. Non-Combining Units

1. Prefix and suffix units do not combine
2. Certain internal C and V units are also unbreakable (e.g., QU)

Table 6

Example 1

Unit Detection

R E Q U I R E

R E (Prefix)

Q U (Not Splittable)

U I

I R

E

Perceptual Parsing

R E	Q U	I R	E
P	C	V	V

Syllabication

R E Q U I R E

(Correct)

Table 7

Example 2

Unit Detection

DECLINATION
DE
CL
IN
AT
TION
Overlapping,
ION
ON
Subsumed

Perceptual Parsing

DE	CL	IN	A	TION
V	C	V	V	S

Syllabication

DE CLIN A TION

(Dictionary says the correct syllabication is: DEC - LI - NA - TION)

Table 8

Example 3

Unit Identification

ENLISTMENT

EN

L

IS (Subsumed)

IST

MENT

EN (Subsumed)

Perceptual Parsing

EN	L	IST	MENT
V	C	V	S

Syllabication

EN LIST MENT

(Correct)

were correct and 64% of the syllables were correct. The discrepancy between the two vocabularies can be explained by the greater number of plural and past tense forms and compound words on the System-D list. The final units list contained 224 items.

Based on the results of the PARSYL program, 80 of the 224 units were chosen to be tested and ranked according to their relative difficulty in the BANDWIDTH experiment. They would then be used for training in perceptual unit identification. Selection of these units was based upon frequency of unit occurrence in the test vocabularies and association of units with successfully distinguished syllables. The final list of 80 units is given in Table 9. Appendix A contains the 224 units and shows the distribution of units by prefix, suffix, vocalic and consonant groups.

Stimulus word lists. Stimulus words for each unit trained consist of the following types of words: forty test words that contain the unit to be trained; fifteen filler words (high confusability words) which share a high degree of similarity to the test words based on unit resemblance (e.g., "gen" becomes "gem," "ger," "pen," etc.), word length, and whole-word configuration (e.g., "genuine" becomes "germane," with descenders and/or ascenders occurring in the same position); and another fifteen filler words classified as dissimilar, in that the words bear no resemblance to those containing the unit except in word length (Appendix B).

Equipment. The equipment consists of an Exidy Sorcerer Microcomputer with 32K Ram and a Leedex 100 Video Display. The Sorcerer is equipped with an S100 Expansion Bus, a Micromation dual 8" disk drive and disk controller, and supports the CP/M system.

All instructional systems are implemented using CP/M

Table 9

Units Used in Perceptual Units Training

1	un	an	ly	re
2	ac	be	th	ab
3	ism	ing	cl	ure
4	tion	ist	ence	ish
5	ty	ter	ous	ound
6	ble	ple	ite	di
7	age	ace	pre	ful
8	ate	sp	con	ent
9	br	ph	for	ness
10	pl	ash	gen	bit
11	pro	ight	min	ize
12	com	eck	por	cal
13	ick	ord	ast	ance
14	and	ile	tr	ven
15	ire	ex	ler	im
16	sh	ob	bi	il
17	mis	ake	as	sion
18	der	col	sive	ale
19	less	sen	sin	wh
20	de	ver	ock	ant

These four columns represent the 80 units which were used in Perceptual Units Training. Units were assigned to one of four groups. Each group contained 20 units. Every effort was made to match each group according to length, positional likelihood, and frequency of occurrence. Five units in each group (located below the dotted line) were designated as control units. Thus, only the 60 units above the dotted line were actually used as training units.

Extended Basic although the programs contain several Z-80 machine language subroutines for purposes of displaying stimulus material and timing keyboard responses. The stimulus materials used by the instructional programs are contained in separate CP/M data files. Records of subjects' performances are updated at each session and maintained as CP/M files as well.

Instructional Principles and Procedures

We now discuss the principles and procedures of Perceptual Units Training. Several general principles served to guide training. Specific procedures evolved as training progressed, and these reflected individual student differences. Certain a priori principles stemmed directly from the constraints of learning psychology which informed our instructional plan. These represented the most general guidelines and applied across all training sessions for all students. Before actual training had begun, for example, we knew that motivation would play its part and contribute to performance. We therefore decided to provide what we judged to be reliable opportunities for success through guidelines on the order of unit presentation. We also knew that there would be need for concentrated periods of practice. However, until we had actual performance data, we could not specify the dimensions of optimal practice. Careful monitoring of student progress enabled us to observe and specify these dimensions and from them to generate a training methodology based on actual performance characteristics.

A set of performance-based principles and procedures evolved in this way and these provided the richest information about effective instructional procedures. They reflected what we had learned about the dimensions of optimal practice on the basis of student performance, including the frequency and intensity of practice and the sequencing of units during a training session. The appropriateness of these guidelines was validated by the effects that resulted from their application. That is, when the effects of a specific performance-based instructional decision stabilized, if they stabilized at all, the guideline was confirmed. In this sense, each training session served as a replication or extension of previous sessions. Finally, because ours is a theory of individual differences, a third and narrower set of principles evolved for determining individual criterion speed and accuracy rates for beginning and terminating training on units. These were designed to be flexible and were adjusted as needed. In this way, they always reflected an individual's current level of performance. In training, then, each trainee effectively served as his own control, and there were built-in tests of the training procedures. Thus, the different levels of our training features and procedures served as checks on themselves and each other.

Since it was through the trainees themselves that the efficacy of our instructional plan was tested, we include here some basic information about them so as to anchor the discussion that follows. Our subjects were four high school students who represented the two lowest quartiles of our sample, as measured by the Nelson-Denny Reading Test Total score. The four students were trained in pairs. In the first pair we had Jim and Mario, who were ranked at the 10th and 29th percentiles, respectively. In the second pair, we had Tracy and Jane who were similarly ranked at the 9th and 23rd percentiles.

Jim and Mario provided us with our first look at individual performance differences. They differed in interesting ways, most markedly during the early stages of training. Whereas Mario typically established his criterion speed and accuracy rates by his third or fourth trial, Jim would often require ten or more trials on a given unit to reach criterion. Clearly, these differences called for different instructional procedures and it was performance differences such as these that led to the flexible training procedures we developed. Tracy, and to a lesser extent, Jane, provided us with a second look at the effectiveness of the procedures we had generated in response to the performances of Jim and Mario. Unquestionably, it is too soon to propose a "group profile" for training. But the differences we observed, if they are true of others of similar ability, do suggest different training strategies based on differences in reading performance.

Our training principles and procedures focused on five factors: the selection and grouping of units, the sequencing of units, the frequency and intensity of practice, the determination of performance criteria, and the maintenance of criterion-level performance.

Selecting and grouping units for training. In grouping units for training, we began with two general assumptions: that high frequency units in highly predictable positions would be easiest to train, and that as frequency of occurrence and positional likelihood decreased, unit difficulty would increase. For the purposes of training, therefore, unit difficulty was characterized along two dimensions: frequency of occurrence and positional likelihood (likelihood of occurring in initial, final, or medial positions in words). However, since relative difficulty varied for individual trainees, a difficulty index was derived from the BANDWIDTH experimental data.

In the BANDWIDTH experiment, a unit was presented, followed by a series of stimulus words, some of which contained the target unit. Mean RTs over those stimulus words were calculated for each unit. For each trainee the units were ordered on mean RT and this constituted the individual's ranking of units by difficulty.

Units were classified as hard or easy on the basis of the calculated unit difficulty rankings, taking into account as well, the frequency with which units occurred in difficult medial positions within the stimulus words. In the early stages of training, both easy and hard units were included in every session. Grouping units according to their ease or difficulty ensured that students would experience success as well as challenge. Our classification of units as hard or easy was clearly reflected in their ease of acquisition during training. For all four students, for example, the unit cl (which occurs reliably at the beginning of words in the inspection list) proved relatively easy and was enthusiastically received whenever it appeared. By contrast, gen (which was unpredictable) proved less tractable, but instructionally more challenging. Unit difficulty was also sometimes reflected in the degree of accuracy of detection. One of our subjects, for example, was fast and accurate on most early units, but on gen he was consistently less accurate. This early inaccuracy on gen ultimately manifested itself as a failure to increase speed at the rate he was able to do on other units (See our discussion of Figures 11A and 11B in Results section).

The need to construct strictly balanced sets of units became unnecessary as training progressed and this was due to the success of training itself. That is, students not only acquired units in much less time, but their performances on easy and difficult units became indistinguishable, with a few exceptions. In other words, they effectively widened their band of easy units, thus obviating the need to classify units by difficulty.

Sequencing units during training. In sequencing the presentation of units during a training session, we were guided by two general principles. The first principle stated that a session would begin with units which were set to be presented at slow speeds. The first units presented in a session were either new units (because these were set at the lowest speeds) or those old, previously practiced, units that still required practice at slow speeds. The second principle evolved from observations of actual performance and stated that, in the event a student consistently "crashed" on the first trials for a set of units, the second trials on those units would be deferred until later in the session. Typically, the instructional plan for a session prescribed two consecutive trials for a given set of units. However, based on our early experience with Jim who frequently crashed on the first trials for a set of units and rarely recovered on the consecutively presented second trials, we developed the principle of deferring second trials. It was rigorously and successfully applied to Tracy and Jane during their training (See Appendix C).

The development of these principles was driven by two pedagogical concerns: orientation and motivation. By analogy, our task can be thought of in much the same way as a track event. As a performance that depends on speed and dexterity, it is one that calls for warm-up, or orientation period. The fact that our task is designed to train speed in perceiving multiletter units, and not merely demonstrate it, underscores this need. To meet this need we started each session with units set at the lowest speeds.

Both principles reflect our concern with motivation, and more specifically with the occurrence of early success, the continued experience of success, and the avoidance of long runs of failure. The presentation of new units at the slower speeds at the beginning of a session was intended to provide a reliable opportunity for early success. Deferring the second trial on a set which had proved difficult on the first trial was applied in order to circumvent the observed effects of repeated failure on motivation and performance.

General frequency and intensity of practice. Initially, we estimated that a student could adequately practice twelve units in a forty minute session. These twelve units were presented in a set. The units within the set were presented one after another until the set was exhausted. Typically, the set would then be repeated. However, this procedure resulted in some units being practiced only once while others were practiced two or three times. Moreover, data from Jim indicated increased speed as well as accuracy when a unit was practiced more than once per session. By reducing the number of units in a set to eight, more than one trial on each unit was guaranteed, but typically no more than two trials. Jim's performance under these conditions, first with a set of twelve units, then with a set of eight, provided us with important information about a dimension of optimal practice, namely, that units need to be practiced more than once in a forty-minute session. We extended what we learned from observing Jim to our other trainees. In this way, a procedure that developed from observations of an individual evolved into a more general principle regarding optimal practice for all students.

For Jim, some units still proved intractable even with the guarantee of two trials per unit during a session. We decided, therefore, to remove these difficult units from the larger set and to present them either together in a smaller set that would permit more intensive practice or individually for the purpose of massed practice. When this procedure was first implemented in Jim's sixth session, it was designed to be flexible with regard to the number of practice trials on the unit or units. This meant that a unit could be practiced any number of times consecutively, or it could be alternated with a second unit practiced the same number of times. However, when a unit was practiced more than two times, we observed a decrement in Jim's performance (See Appendix D). Therefore, a limit of two or three trials per unit was established and this upper limit, coupled with our earlier decision regarding the lower limits of practice (more than one trial), became the defining condition for optimal practice on units during all subsequent sessions for all students. This revised format illustrates the application of a fundamental principle on which our training is based: that increased speed and accuracy can be best assured by discovering the optimal conditions for practice. Optimal repetition, in turn, leads to a consolidation in performance which presumably reflects the student's developing skill at quickly and accurately perceiving the units as units, that is, as organized chunks.

On the basis of our experience with Jim, then, we were able to define the conditions for optimal practice. For new units or those units still set at the lower goal speeds, two trials would be provided. In those cases where a student was just short of criterion, one trial was provided (See Determining performance criteria). These procedures were generally applied in all sessions for all students.

There were occasions when a student would encounter difficulty with an entire set of units on the first trial. The difficulty arose from any one of three sources: (1) the units were hard; (2) the goal speeds for the set were very demanding; or (3) the student was not motivated to perform. In such cases, one of two options was available. We either deferred the second trials on the set until later in the session or we did not run the set again in that session.

When the units were hard, we generally chose to defer the second trials until later in the session because this allowed the student to practice and consolidate gains on other easier sets before attempting a second trial on the hard set. This procedure therefore left open the possibility for a "warm-up" effect during a training session. When the goal speeds for a set proved too demanding we again deferred the second trials until later in the session and for the reason offered above. It is important to note here that speed, and not unit difficulty per se, was the critical variable. The student had already demonstrated proficiency on these units and now needed to build up to the more demanding goal speeds. Lack of motivation on the part of the student for practicing a particular set of units overrode any other source of difficulty and was typically not remediable during a session. We therefore chose not to run the set a second time for the reason that the likely effect of doing so would be to further depress the student's motivation and performance for other sets in the session.

Determining performance criteria. The criteria for terminating training on individual units were different for each of the participating students, but were consistent with the overall goal of training which was to achieve a balance between speed and accuracy. Individual criterion speed and accuracy rates evolved during the initial stages of training on the basis of a student's ongoing performance and were adjusted as progress warranted. Specifically, at the start of training, the student's highest winning speed on easy units was used as the criterion for performance on more difficult units. In making this determination we were guided by the purpose underlying our training, namely, to train the student to be as fast and accurate on hard units as he or she was on easy units.

At the beginning of training, the first trials on units were started at a speed of 60 (1000 msec per item in the list) with a corresponding goal speed of 110 (545 msec per item in the list). We estimated that at this starting speed students would be quick to establish their own starting levels within the first trial or two on a new unit and their own criterion levels on subsequent trials. It was in this sense that students established their own criterion for terminating training on a unit. Both starting and criterion levels were adjusted on the basis of a student's ongoing performance. Jim, for example, had an initial criterion speed of 120 (500 msec per item in the list). Although Jim performed successfully at goal speeds above 120, he was quite inaccurate at these levels. This criterion of 120 was therefore intended to encourage him to improve his accuracy while making modest speed demands. Later in training (Session 14), the level of Jim's performance changed markedly (See Results: Records of training). He consistently exceeded 120 without sacrificing accuracy and thereby established new criterion speeds of 130-150 (462 to 400 msec per item in the list). On the basis of this change, we increased his starting speed to 70 and later to 80 because he was now acquiring new units rapidly and accurately.

In contrast, from the outset of training, Mario acquired units quickly. By his third session, he established a criterion speed of 180-200 (333 to 300 msec per item in the list) across all unit types. His rapid rates of acquisition and high levels of speed resulted in regular increments of his starting speeds to a ceiling of 120.

Maintenance testing. We have a primary interest in the stability of a student's gains on particular units after criterion is reached and training on those units has terminated. To learn whether gains on speed and accuracy were maintained, maintenance checks were regularly performed. These checks functioned as curriculum-embedded posttests whose purpose was to indicate whether the student had maintained criterion levels of performance on particular units after a lapse of from 5-8 sessions on those units. If the subjects performed at or very near criterion on the maintenance trial, this was taken as evidence that the units had received sufficient practice and that the gains on these units were stable over time.

Criterion Measures

We administered three criterion tasks to our trainees. Measures derived from these tasks allowed us to evaluate the performance gains on the perceptual skill we were training and the transfer of those gains to other reading tasks along the lines suggested by the interactive model.

1. Unit detection task (BANDWIDTH experiment). The first criterion task provided a measure directly related to the objective of our training. A target unit was first presented, followed by an inspection list of 70 words, 40 of which contained the target unit and the remaining 30 of which were distractors. The distribution of unit positions within the inspection list was controlled to reflect positional likelihoods in a more extended corpus of words. Words varied in length ranging from 4 to 18 letters. At a viewing distance of 22 inches, each letter space represented 18 minutes of visual angle. Each target unit was presented on the Leedex 100 Video Monitor for 150 msec, and was followed by a visual mask which was also exposed for 150 msec.

Subjects responded to each stimulus (inspection unit) by pressing one of two response keys, indicating if the unit was present or absent. Reaction times for each unit detection were measured by the Sorcerer microcomputer using a Z-80 machine language timing loop, to an accuracy of 6 msec. Correctness of the subject's response was also recorded.

Since in this experiment individual RTs were measured for each detection trial, it was possible to analyze mean RT as a function of word length and unit position within a word. Finally, as we have obtained data for a larger sample of 20 subjects representing four reading ability groups, results from this criterion measure can be compared with normative performance levels for those groups of readers.

2. Pseudoword pronunciation task. The second criterion task was a pseudoword pronunciation task (Frederiksen, 1978) in which subjects were asked to pronounce pseudoword items that had been derived from actual English words by changing a single vowel or vowel digraph (e.g, BRENCH, derived from BRANCH). The set of pseudowords included 19 orthographic forms, including variations in length (4, 5, or 6 letters), number of syllables (1 or 2), and type of vowel (simple vowel, vowel digraph, silent -e marker). With eight representatives of each form, beginning with each of eight phonemes, there were in all 152 stimulus items. Stimuli were presented on the screen of the video monitor. They subtended visual angles ranging from 1°14' (4-letter items to 1°50' (6-letter items) at a viewing distance of 22", which was the approximate distance for our subjects. Stimuli were presented for a duration of 200 msec. Subject's vocal reaction times were measured from the onset of the stimulus to the onset of vocalization, using a Grason-Stadler Model E7300A-1 voice-operated relay interfaced to the Sorcerer microcomputer. Reaction times were measured by the microcomputer using a machine language timing loop; individual RTs were timed to an accuracy of 6 msec. Each response was also rated on the basis of correctness of decoding by the experimenter, and results were summarized using two statistics: mean RT for correct pronunciations and percentage of correct responses.

3. Span of apprehension task. Our third criterion task permitted us to measure the span of apprehension--the width of the effective visual field--for a target phrase, presented alone, or as the completion of a context phrase. As shown in Figure 8, our subjects view a series of displays on the screen of the Leedex Monitor, each of which is made up of 3 frames. Frame 1 contains a context paragraph. Subjects read the paragraph at their own rate. When they reach the end, they are asked to fixate a spot appearing in the final line of the display and to

Frame 1

They notice that the heat changes from hour to hour. So the day is carefully planned. They know it is hottest during the afternoon. So they do not work then. Instead, they rest. They may take a nap. As

Frame 2

,

Frame 3

a rule they do their jobs later.

Figure 8. The sequence of displays used in the context condition. Frame 1 contains the context and is subject terminated. Frame 2, presented for 200 msec, contains the fixation point. Frame 3 contains the test phrase, and is also presented for 200 msec.

press a response key. Frame 2 is then presented for 200 msec followed by the test phrase in frame 3, also for 200 msec. The subject's task is to report as many words or word fragments as he can see in the test line. The subject's response was typed by the experimenter, and transferred into a Sorcerer CP/M disk file. The response measure was the distance in letter spaces from the left-most to the right-most correct letter of the phrase. Vocal onset RT was also measured and recorded.

In each session, subjects were presented a total of 40 test phrases for which a context passage was presented prior to the test exposure, and 40 test phrases in which the prior context passage was omitted. The passages used in the experimental task were taken from the Degrees of Reading Power Test (State of New York, Board of Regents, 1976, Forms X and Y). The test passages covered five levels of text readability, chosen to represent approximately equal steps on the Bormuth scale. For each readability level, there were two sets of eight consecutive test passages that together made up a mini-essay on some topic of general interest. One of these mini-essays was assigned to the context condition, and the other to the no-context condition.

Our measure of the subject's ability to encode words within a single fixation was the mean visual span for test phrases presented without accompanying context. Our measure of the subject's ability to utilize context was the *increase* in visual span when a prior context was provided. Positive values indicate that a subject can profit from such context. Negative values indicate disruption in word recognition processing when a concomitant comprehension task is required.

Subjects

The four students we trained attended a public high school in Cambridge, Massachusetts. They were selected for training from a pool of twenty subjects who had participated in an earlier experiment (BANDWIDTH). The twenty subjects were explicitly chosen to represent a wide range of reading abilities, as defined by percentile scores on the Nelson-Denny Reading Test Total score (a composite of vocabulary and comprehension items). Percentile scores for the sample ranged from ninth to ninety-ninth. The median percentile score in our sample was 62. Grouping the subjects into four reading "levels" resulted in the following distribution of scores:

Group I	9-12%-ile
Group II	22-59%-ile
Group III	66-79%-ile
Group IV	94-99%-ile

In order to maximize the information we could obtain from our students, we worked with them in pairs. Within each pair we included one student from Group I and one from Group II so that they would reflect two types of poor readers as measured by the Nelson-Denny. The first two students, Jim (10th percentile) and Mario (29th percentile), provided a powerful comparison of training procedures and effects. They also served as the standard against which to undertake, implement, and evaluate training on the second pair of trainees, Tracy (9th percentile) and Jane (23rd percentile). This second training effort was hampered because of competition with school closing. Jane was unable to complete training because of full-time employment, and Tracy was terminated after training on 46 of the intended 60 units also because of employment. We were therefore left with a counterpart to Jim only, and not an ideal one. Nonetheless, we were able to gain useful insights into the nature and scope of individual differences in performance on the training task.

Results

In this section, we present the records of progress and the results of Perceptual Units Training as reflected on the training task itself and on the criterion performance measures. Measures of progress on the training task will be presented for individual students and at several levels of detail. At the finest level, we report learning records on a trial-by-trial basis for selected units representative of difficult, moderately difficult, and easy units, and these are presented for different periods within the training sequence. At a coarser level, we present selected statistics descriptive of the acquisition rate and performance levels for each of the students on all of the units in the order in which they were trained. We shall also present records for maintenance testing of each unit trained for each of the students. These summary statistics serve to illustrate the changes in learning rate and performance over the course of training as well as the stability of gains in speed over time. We first present the results for our initial pair of trainees, Jim (10th percentile) and Mario (29th percentile). We then present the performance records for our second pair of trainees, Tracy (9th percentile) and Jane (23rd percentile).

In the final section, we discuss the pre- and post-test results for the criterion measures of perceptual unit identification (the unit detection task, BANDWIDTH), decoding automaticity (the pseudoword decoding task), and word recognition in and out of context (the span of apprehension task).

Records of Training: Jim and Mario

We shall begin by focussing on the most salient features of change in performance over the course of a training sequence. The features we consider include changes in the rate of unit acquisition (number of trials to reach criterion), in levels of performance (final rates of speed), and in response to unit difficulty. In this way, we can offer a view of the overall effects of training for all four students while focussing principally on individual performances and student comparisons over time. We begin with a contrastive description of the performances of Jim and Mario, followed by one for Tracy and Jane.

In Figure 9A, we present a plot of Jim's performance on three representative units (cl, pre, ast) practiced during the first ten training sessions. The difficulty level of a unit reflects the rate at which students acquired the unit in actual training. One of the most striking features of this picture is the large number of trials, ranging from 10 to 14, that Jim needed in order to establish his first-order criterion (120). His criterion was set at 120 because as Figure 9A indicates, above that speed, Jim's performance was consistently inaccurate. For Jim, acquiring new units at the outset of training was especially effortful. Small gains were often followed by dips in performance as shown in trial 4 on pre, trials 6 through 8 on ast, and trials 8 through 9 on cl. Another striking feature is the difference in performance on cl and the other units in the figure. While on cl Jim succeeded at a goal speed of 110 on the first trial and showed gradual but continual improvement on the unit, on pre and ast he struggled to reach the same or higher speed. On ast, he exceeded 110 on the eleventh trial, and on pre on the fifth trial. This differential performance on units illustrates the narrow unit Bandwidth typical of the poor reader, with few units classifiable as easy. Of note, too, is the sudden steep slope on cl and ast beginning at the ninth and eighth trials, respectively. The steep slope signifies that Jim is getting faster in fewer trials. On ast, for example, he gains approximately 60 units of speed in four consecutive trials (8-11) as compared with a gain of a little over 20 units in trials 1 through 6. The levelling off in speed for pre, beginning at the ninth trial, coincides with our decision to provide massed

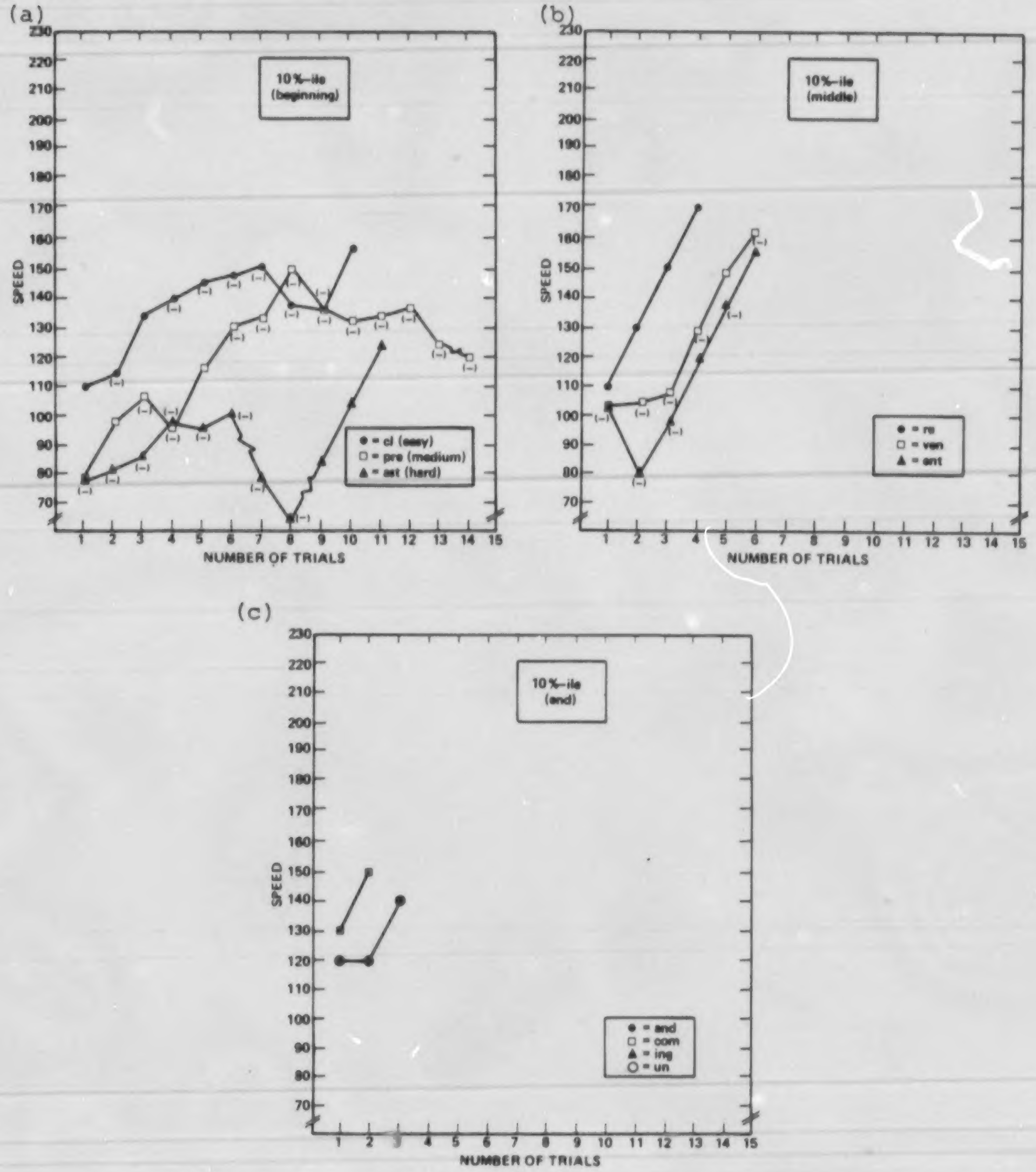


Figure 9. Performance records for Jim on representative units at beginning (a), middle (b) and end of training.

practice without having yet placed a limit on the number of consecutive practice trials. The effect of too much practice is evident for pre on trials 9 through 14. Jim gains little as consecutive trials are added and even drops off on the eleventh trial.

By way of contrast, in Figure 10A, we present Mario's performance at the beginning of training (Sessions 1-3). Mario acquires new units in half the number of trials that Jim does and at considerably higher speeds (170-190). In addition, the units are barely distinguishable on difficulty, although th falls off on the sixth trial.

In Figures 11A and 11B, the two students are compared on two units, cl and gen, presented to both at the beginning of training. These figures dramatically illustrate the differences between the two boys during the early stages of training on an easy unit (cl) and a hard unit (gen). Mario rapidly acquires cl while Jim makes more gradual progress. On gen, Mario quickly progresses in the first three trials, gradually improves in trials 3 through 7, and then reestablishes his early rate of improvement in trial 8. Jim is slower to acquire gen than cl, but the overall shape of performance is much the same with a sharp rise in slope in the later trials.

During the early stages of training, then, Jim and Mario present strikingly different profiles. Indeed, they differ on every important dimension: rate of unit acquisition, level of performance, and unit difficulty. Jim requires twice as many trials as Mario to establish a markedly lower criterion. He also shows a large effect of unit difficulty at all speeds while Mario shows a similar effect only at higher speeds and on units whose positional likelihood is variable (at 150 on gen and at 170 on th).

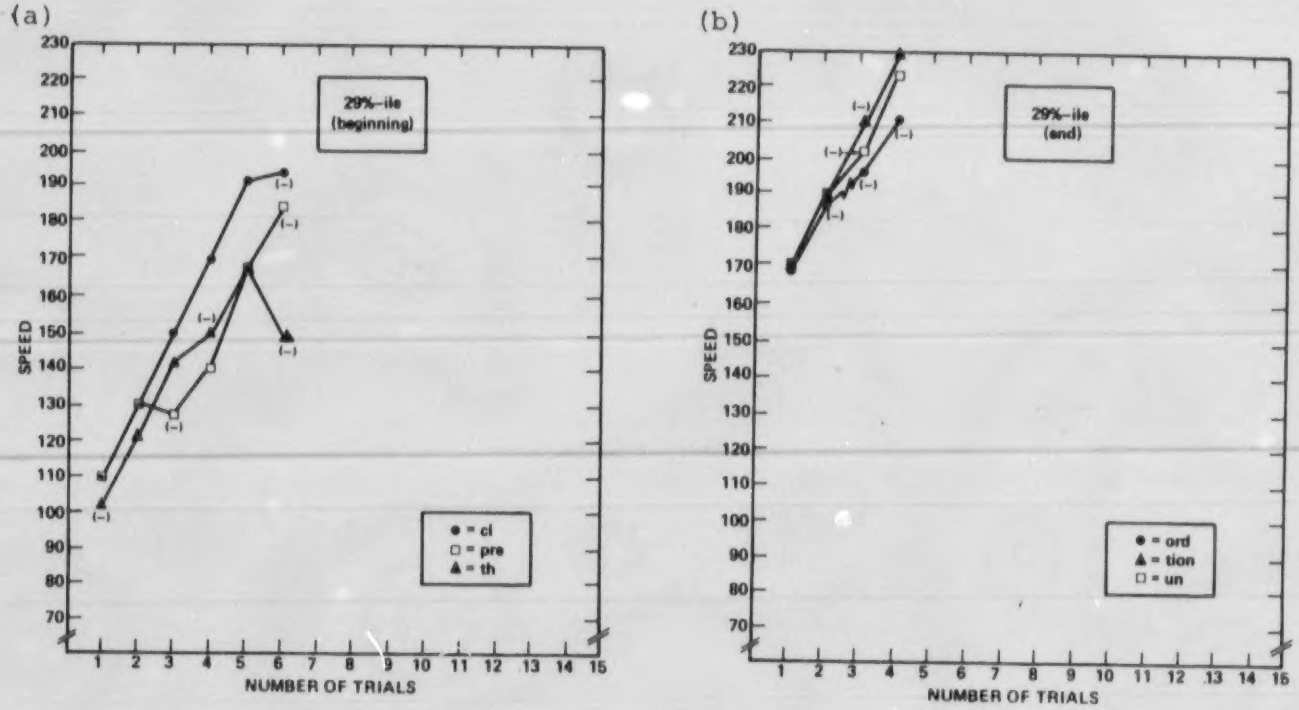


Figure 10. Performance records for Mario on representative units at beginning (a) and end (b) of training.

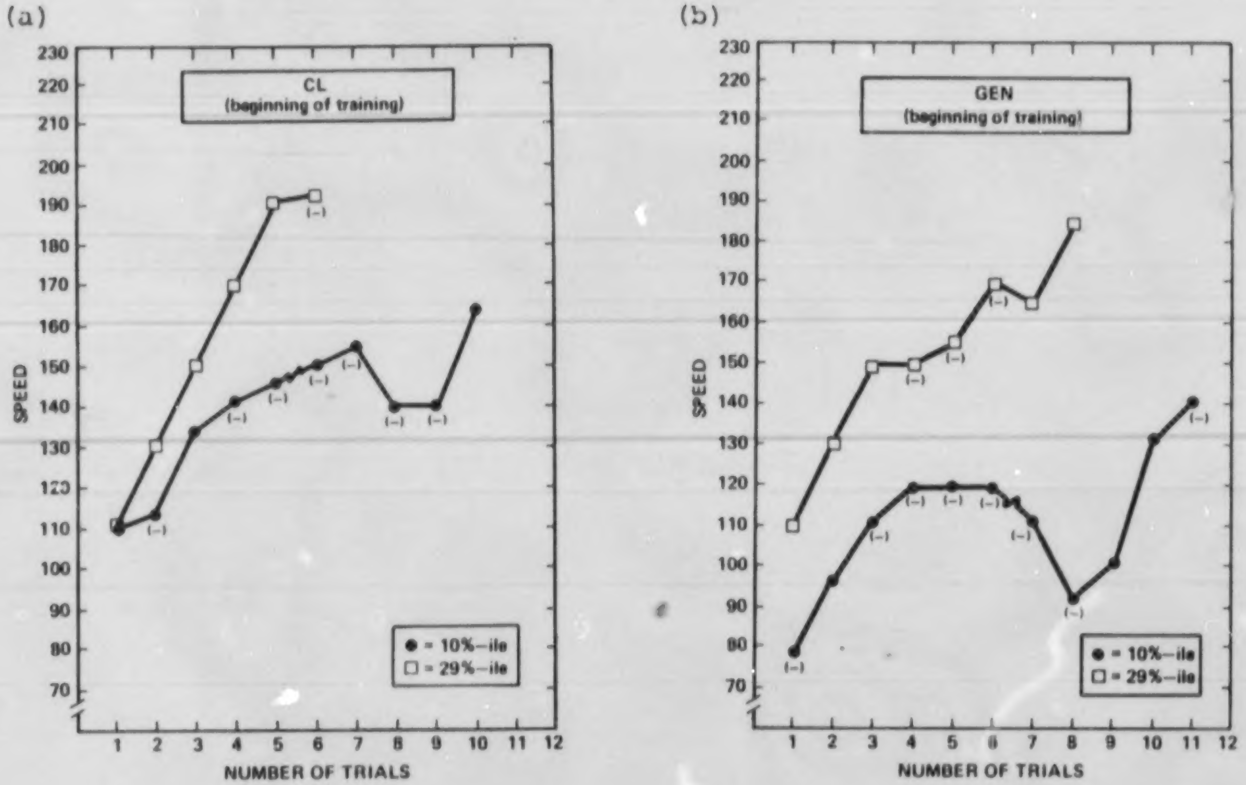


Figure 11. Reader performances for Jim (10th percentile) and Mario (29th percentile) compared (beginning of training).

By the middle of training (Sessions 11-15), a different picture emerges for Jim. In Figure 9B, it is clear that rapid acquisition of new units is more the rule than the exception. Specifically, Jim has cut the number of trials he needs to acquire units by about half and is in some cases reaching higher speeds (160-170 on re and ven). An effect of unit difficulty is still observable, though somewhat attenuated. On re, Jim performed perfectly, reaching each preset goal speed on four consecutive trials. On ven and ent, Jim required from two to three trials before he performed as consistently as he did on re. As a unit occurring reliably at the beginning of words, re is comparable to cl (Figure 9A) and provides a striking picture of the degree of improvement on such units. Similarly, the plot for ven, a unit having variable position, illustrates the improvement in his performance as compared with such early units as ast and gen.

In general, Jim begins to look more like Mario (Figures 12A and 12B), although Mario is now starting at higher goal speeds (140-150) with the result that he is reaching criterion in still fewer trials. Similarly, in Figure 12B, Jim's starting goal speed has increased from 110 to 120, and he reaches 160 in three consecutive trials. Mario is nearly twice as fast in his overall performance level as Jim. But, they both acquire units rapidly.

To summarize, in the middle stages of training the look of Jim's performance changes dramatically. He reaches a higher criterion in fewer trials than he did during the early stages, and units are not as distinguishable on unit difficulty. Mario has changed less, although his starting goal speeds have increased from 110 to 150 and then 170, resulting in fewer trials to reach criterion. By Session 15, Jim is also starting at a higher goal speed, 120, up ten units from his initial 110. In Figures 12A and 12B, Jim's performance very nearly parallels that of Mario's.

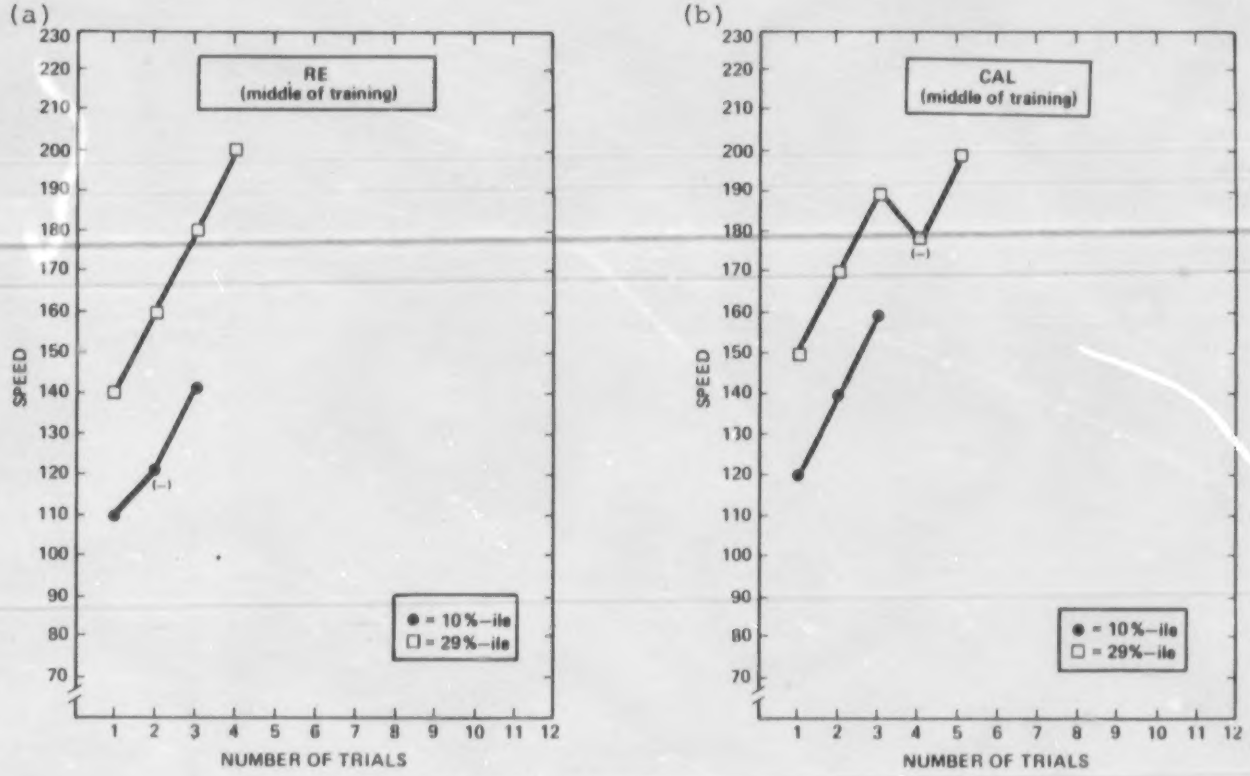


Figure 12. Reader performances for Jim (10th percentile) and Mario (29th percentile) compared (middle of training).

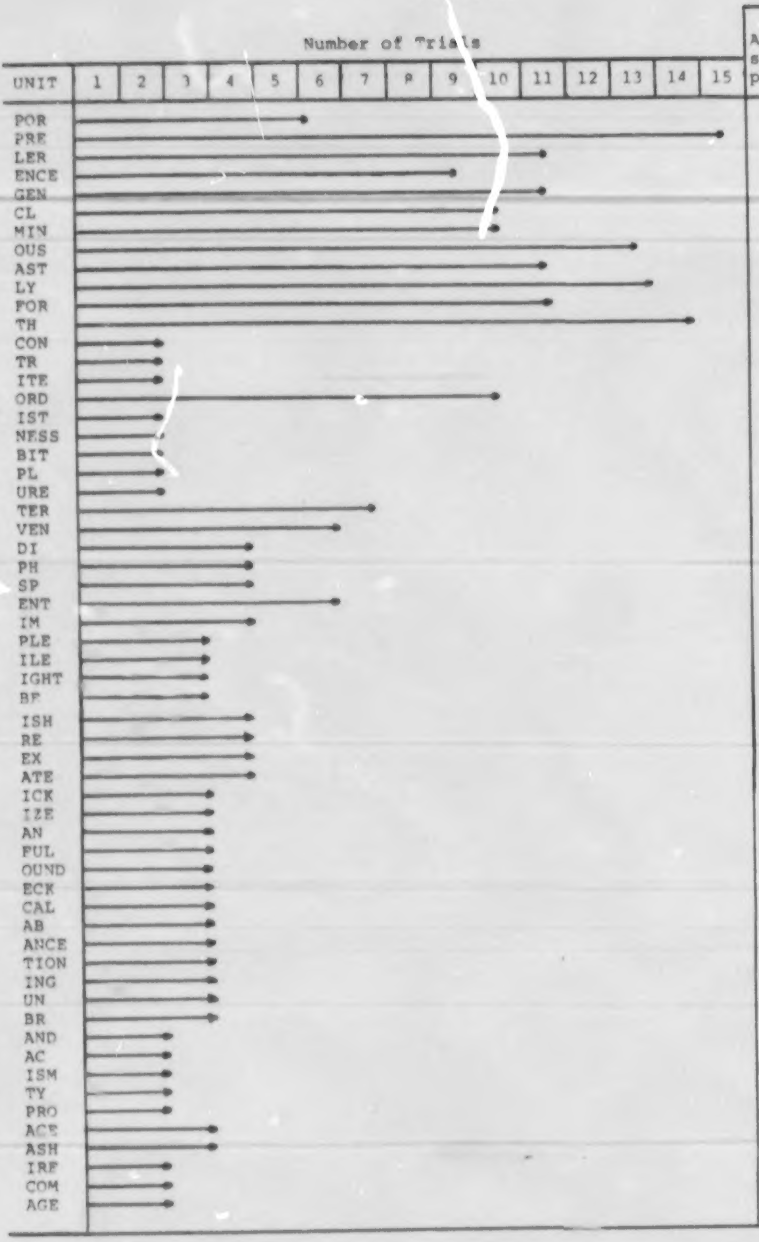
The stability of Jim's performance from the middle of training to the end is most strikingly represented in Figure 9C. By the end of training, Jim is starting some units at a still higher goal speed (130) and he has effectively reduced the number of trials he needs to reach criterion to two or three. Moreover, Figure 9C presents two plots which actually depict performance on four units. Comparing this overlapping picture with Figure 9A illustrates the extent to which Jim's performance has improved and consolidated. The plots in Figure 9A for three units are sprawling whereas those in Figure 9C are compact.

For his part, Mario continues to accelerate, as shown in Figure 10B, and begins these late training units at a starting goal speed of 170. The comparisons of Figures 9C and 10B illustrate end-of-training performance for Jim and Mario. While they differ in final levels of performance attained, their rates of acquisition are remarkably alike, continuing the trend they displayed during the middle stages of training.

The results we have reviewed for selected units suggest certain summary statistics that can be used to describe compactly the performance for all units in the sequence in which they were learned. In Tables 10 and 12, we present the total number of trials that Jim and Mario required to learn the units. We view these tables as primarily reflecting rates of acquisition for units, although they are influenced by individual differences in criterion rates of speed. For these reasons, the tables permit comparison within subjects across trials as well as between subjects. In making between-subject comparisons, the specific criteria employed must be taken into account. In Tables 11 and 13, we represent the range and plot the lowest and highest speeds attained. The lowest speed generally reflects a student's initial performance level (it is the speed attained on the initial training trial or on a subsequent trial in cases where the goal speed on the initial trial was too stringent). The

Table 10

(10%-ile)



UNIT	Average speed per unit	Maximum winning speed	Maint. speed
POR	112	126	126
PRE	121	126	126
LER	116	133	117
ENCE	108	138	138
GEN	112	157	157
CL	137	157	157
MIN	103	122	94
OUS	116	122	94
AST	99	125	97
LY	131	118	118
FOR	134	162	140
TH	129	140	140
CON	120	130	130
TR	120	130	130
ITE	120	130	130
ORD	119	150	128
IST	120	130	130
NESS	120	130	130
BIT	120	130	130
PL	120	130	130
URE	120	130	120
TER	109	136	136
VEN	103	148	148
DI	120	110	110
PH	120	130	130
SP	120	130	130
ENT	115	156	156
IM	120	130	130
PLE	116	136	104
ILE	127	130	130
IGHT	130	151	151
BF	128	142	142
ISH	131	150	142
RE	140	170	270
EX	140	170	170
ATE	136	162	162
ICK	140	160	160
IZE	136	156	156
AN	140	160	160
FUL	140	160	152
OUND	140	160	128
ECK	119	134	134
CAL	140	160	156
AB	139	140	140
ANCE	130	136	136
TION	123	140	140
ING	127	140	140
UN	127	140	140
BR	125	140	140
AND	140	150	150
AC	140	150	150
ISM	140	150	150
TY	140	150	150
PRO	140	150	150
ACE	137	130	130
ASH	139	130	130
IRF	140	150	150
COM	140	150	150
AGE	136	146	146

TABLE 11
(10 %—ile)
RANGE OF SPEED)

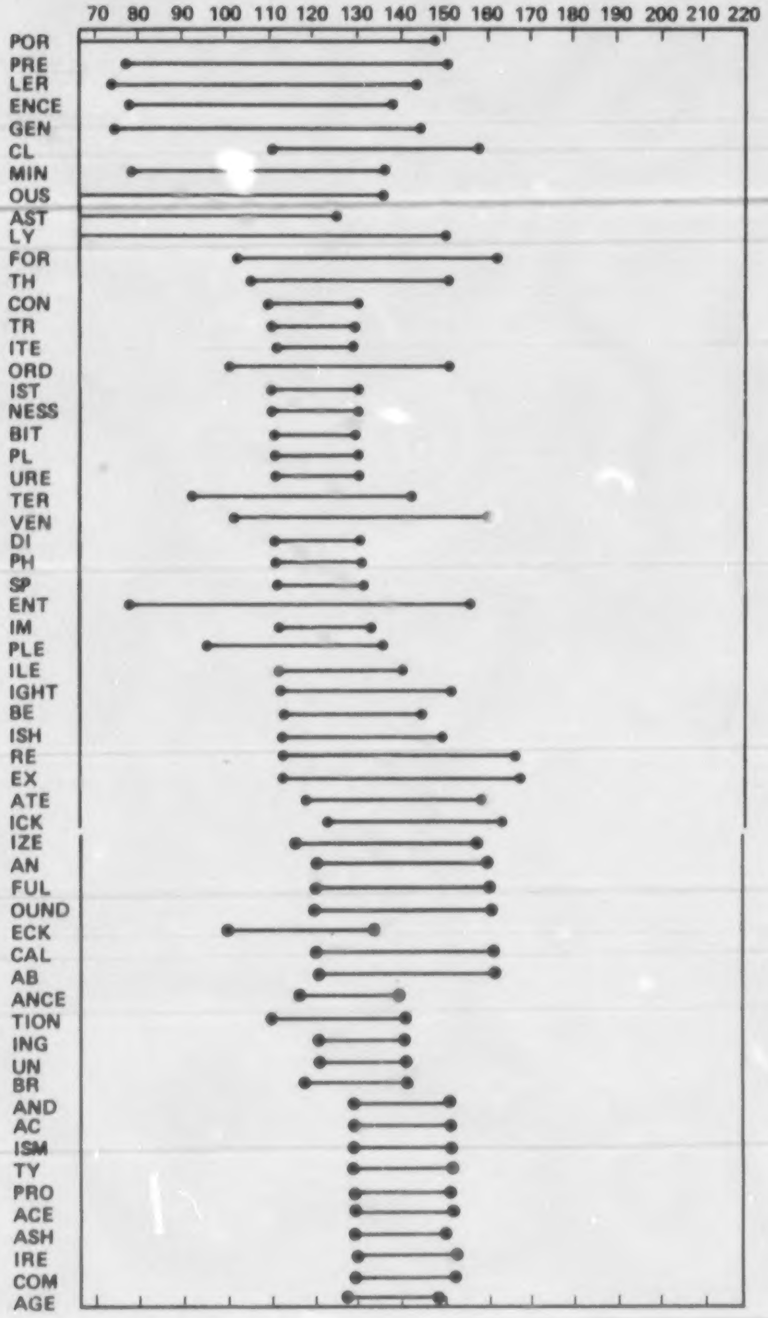
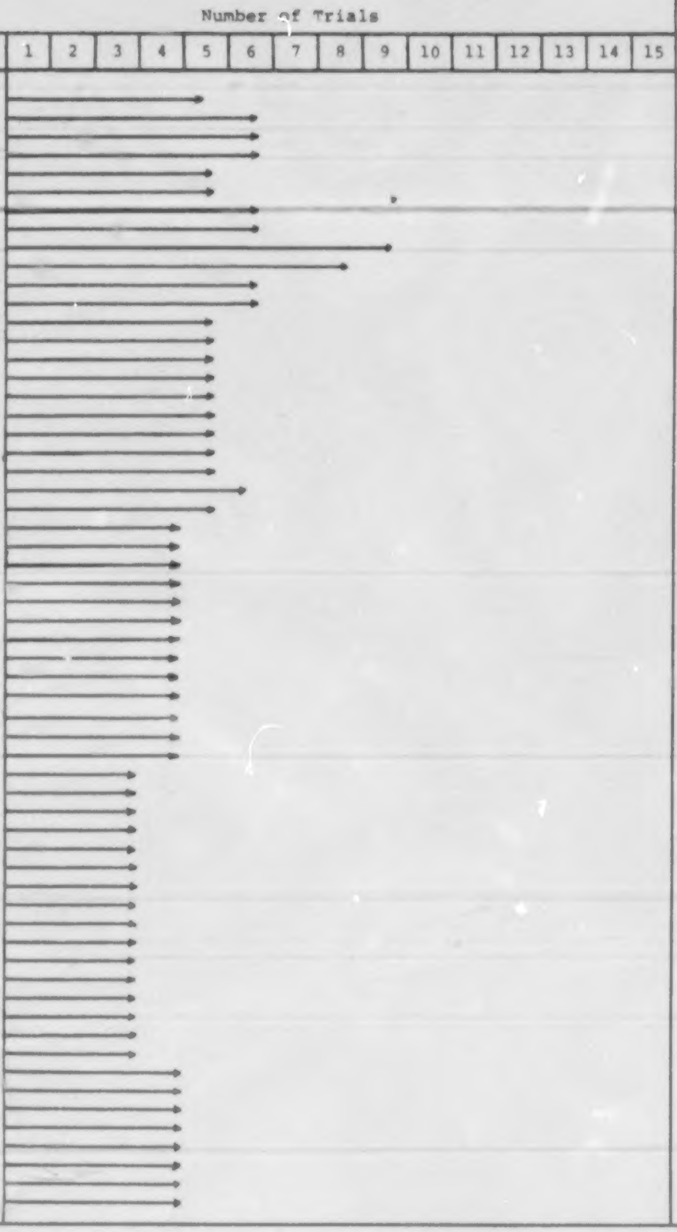


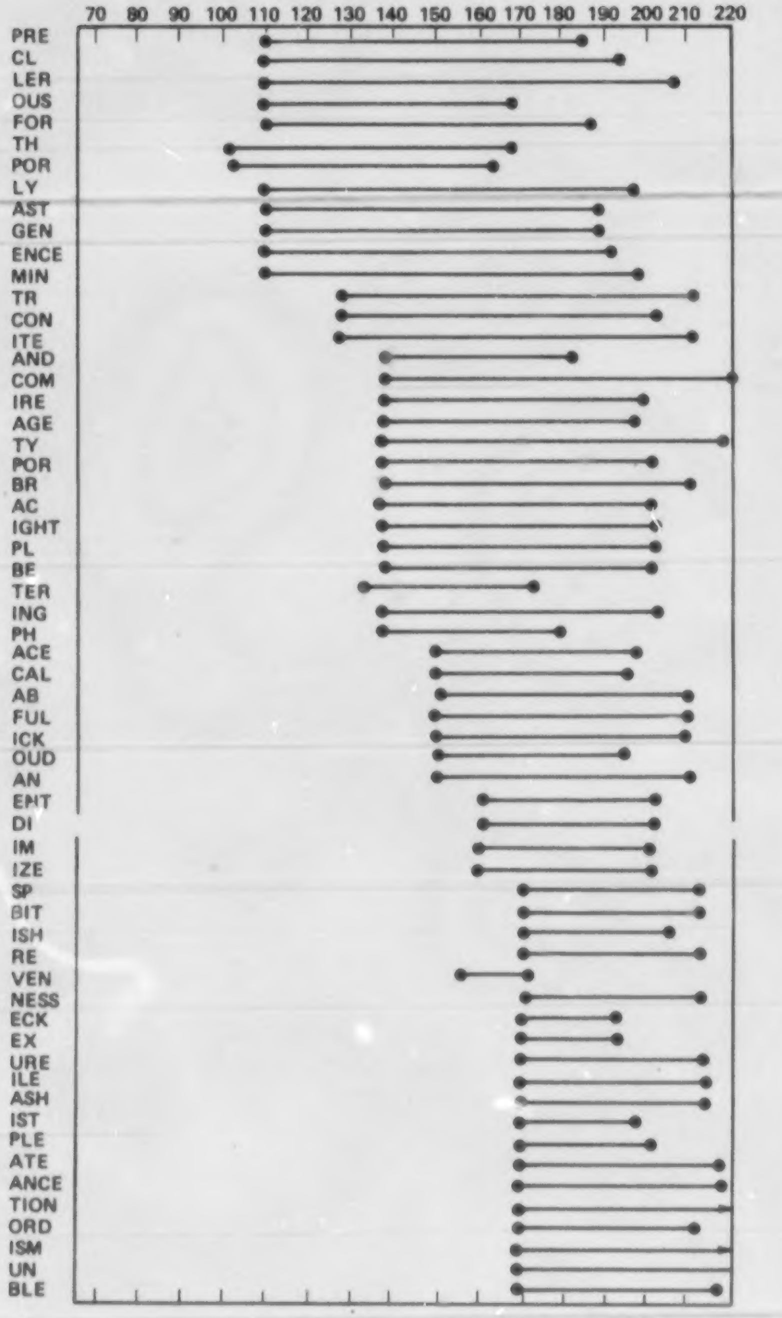
Table 12

(29%-ile)



UNIT	Average speed per unit	Maximum winning speed	Maint. speed
PRE	143.3	168	168
CL	157.0	190	190
LER	157.3	186	186
OUS	141.7	168	168
FOR	149.3	180	180
TH	138.3	168	168
POR	130.0	162	162
LY	157.7	190	190
AST	156.9	186	186
GEN	152.0	186	180
ENCE	154.7	190	188
MIN	157.8	190	190
TR	170.0	210	210
CON	168.4	190	190
ITE	170.0	210	210
AND	162.8	182	182
COM	180.0	220	220
IRE	171.6	198	198
AGE	170.4	196	196
TY	179.6	220	220
PRO	172.8	198	198
BR	180.1	220	214
AC	173.2	206	206
IGHT	170.0	200	200
PL	170.0	200	200
BE	170.0	200	200
TER	155.0	172	172
ING	170.0	200	200
PH	159.5	178	178
ACE	175.0	170	170
CAL	176.4	190	190
AB	180.0	210	198
FUL	180.0	210	210
ICK	180.0	210	210
OUND	176.0	194	194
AN	180.0	210	210
ENT	180.3	201	192
DI	180.0	200	200
IM	180.0	200	200
IZE	180.0	200	200
SP	190.0	210	210
BIT	190.0	210	210
ISH	188.0	190	190
RE	190.0	210	210
VEN	166.0	170	154
NESS	190.0	210	210
ECK	182.0	190	.190
EX	190.0	210	210
URE	190.0	210	210
ILE	190.0	210	210
ASH	190.0	210	210
IST	185.3	190	176
PLE	185.0	200	164
ATE	193.0	216	186
ANCE	196.5	190	172
TION	199.0	220	210
ORD	190.5	170	170
ISM	200.0	230	230
UN	196.0	222	222
BLE	196.0	190	174

TABLE 13
(29 %–ile)
RANGE OF SPEED



highest speed was usually, but not always, the speed on the final trial. It was always the highest winning speed attained. The range is another measure of the rate of acquisition of a unit. The highest speed reflects the maximum performance level for units at various stages in the training sequence.

Rates of acquisition. The evidence for Jim and Mario indicates a substantial reduction in the time required to acquire new units as training progressed. In Tables 10 and 12, there is a progressive reduction in the number of trials needed to acquire new units. Jim required more trials than did Mario at the beginning of training. By the end of training, he took fewer trials than Mario to acquire new units. Bear in mind, however, that Jim's maximum speeds were markedly lower than Mario's. These increases in learning rate are also apparent in the reductions in range illustrated in Tables 11 and 13. This is due primarily to a substantial increase over the course of training in the speeds attained on the first trials of new units. At the beginning of training, Jim's initial performance levels on new units were in the neighborhood of 70-80 items per minute. At the end of training, his initial performance levels were about double that (130 items per minute). Similarly, early in practice, Mario's initial performance level on new units was 110 items per minute, and increased to 170 items per minute at the end of training.

There are a number of possible explanations for these increases in initial performance levels on new, untrained units.

1. Gamesmanship (or strategic aspects of playing the game): Students may be learning a series of adjustments to the gaming environment that enable them to perform efficiently. For instance, they may be learning to maintain attention on targets, utilize peripheral vision to monitor the error lights and

speedometer, adjust their overall performance criteria so as to tolerate some errors in the service of speed, and learn the mapping of fingers to response categories.

2. Tapping prior unit knowledge: Students may be learning to apply prior knowledge of orthographic groupings to the training task. For example, they may have knowledge of unit positional likelihood or orthographic environments in which units might occur that enable them to achieve higher levels of performance on initial trials for new units. Jim, for instance, on the initial trials for new units began by spontaneously generating words containing the target unit.

3. Distribution of attention: Students may be learning to distribute their attention across letter positions within a target item so as to more rapidly detect units in the more difficult medial positions.

Any or all of these factors may account for the improvement over training in the initial performance level on new units.

Maximum performance levels. Jim and Mario's maximum levels of performance on units at the end of six weeks of training differ to some extent from the levels at the start of training (Tables 11 and 13). Jim was initially reaching maximum speeds ranging from 125-150, but was inefficient in that his accuracy rates were low. That is, he would frequently commit errors and have to slow down to erase them before progressing to higher rates of speed. Later in training, he performed accurately and rapidly attained the goal speeds that were set for him. His maximum performance level over the second half of training ranged from 140-160 items per minute. Mario's maximum performance level was in the neighborhood of 165-210 items per minute over the first half of training, and in the range of 190-230 over the second half.

Mario's average maximum speed was 194 items per minute, or 309 msec per item in the list. Jim's average speed was 142 items per minute or 423 msec per item in the list. The value obtained by Jim is quite comparable to those obtained by Tracy and Jane who averaged 140 and 148 items per minute, respectively. Mario's performance level, however, is notably higher than those of the other three students. An explanation for Mario's extremely high performance level may be made in terms of a particular strategy for playing the game. We believe that Mario's error rates for the difficult cases where units were embedded in the middle positions were near-chance level. Mario appeared to tolerate errors in these more difficult cases with the knowledge that within a trial, he could eliminate those errors with correct (error-free) performance when the unit occurred in the easier positions. Evidence bearing on this interpretation is presented in our discussion of training effects on the Criterion Reading tasks, particularly the BANDWIDTH task. That task allowed us to look at accuracy of unit detection at particular positions within the target items.

Maintenance tests. Maintenance tests provide us with a third statistic that describes the stability of gains on each unit over time, specifically, after a lapse of from 5-8 sessions (from 1 to 2 weeks). Jim's average maintenance speed was 137 items per minute. His average speed at the time training on the same items was terminated was 141.5 items per minute. Mario's average speed on maintenance trials was 194 items per minute while his average maximum speed on the same units was 196.8 items per minute. It is safe to say that the gains made in acquiring these units were maintained (see Tables 10 and 12). Further tests of the stability of these gains will be reported in the section on Criterion Reading Tasks.

Records of Training: Tracy and Jane

Tracy (9th percentile) and Jane (23rd percentile) provide us with a second set of comparisons on the effects of Perceptual Units Training. Although training for neither girl was complete, we shall report the training data we have collected. Careful documentation of each student's day-to-day and trial-by-trial performance allows us to take a look at those features of performance which figured so prominently in the preceding discussion of Jim and Mario. These include changes in the number of trials to reach criterion, in rates of speed, and in response to unit difficulty.

Figure 13A depicts Tracy's performance on three representative units, cl, pre, and ast at the beginning of training (Sessions 1-3). In Figure 14, Jane's performance on the same units is plotted. Looking for the moment at cl (an easy unit) and pre (a moderately difficult unit), it is clear that where Jane shows no appreciable effect of unit difficulty, Tracy does. Jane acquires both units in 3 to 4 trials while reaching a criterion of 150. Tracy acquires cl quite readily, but on pre, requires 6 trials to reach a lower criterion of 140. Ast proved difficult for both girls and is certainly one of the least tractable units of the lot. Jane never completed training on it as her struggle to exceed 120 indicates. Tracy, in contrast, struggled through the early trials (1-3). In this respect she parallels Jim, as illustrated in Figure 9A.

In Figures 15A and 15B, Tracy and Jane are compared on two additional units, min and con. While Jane's rate of acquisition of both units was rapid, Tracy required considerably more trials before her performance stabilized. On min, for example, Tracy needed four trials before she levelled off at a high speed of 130 in contrast to Jane who traced a clean, swift path to 150. On con, Tracy actually outstripped Jane on the ninth trial, but of course, required three times as many trials in which to do so.

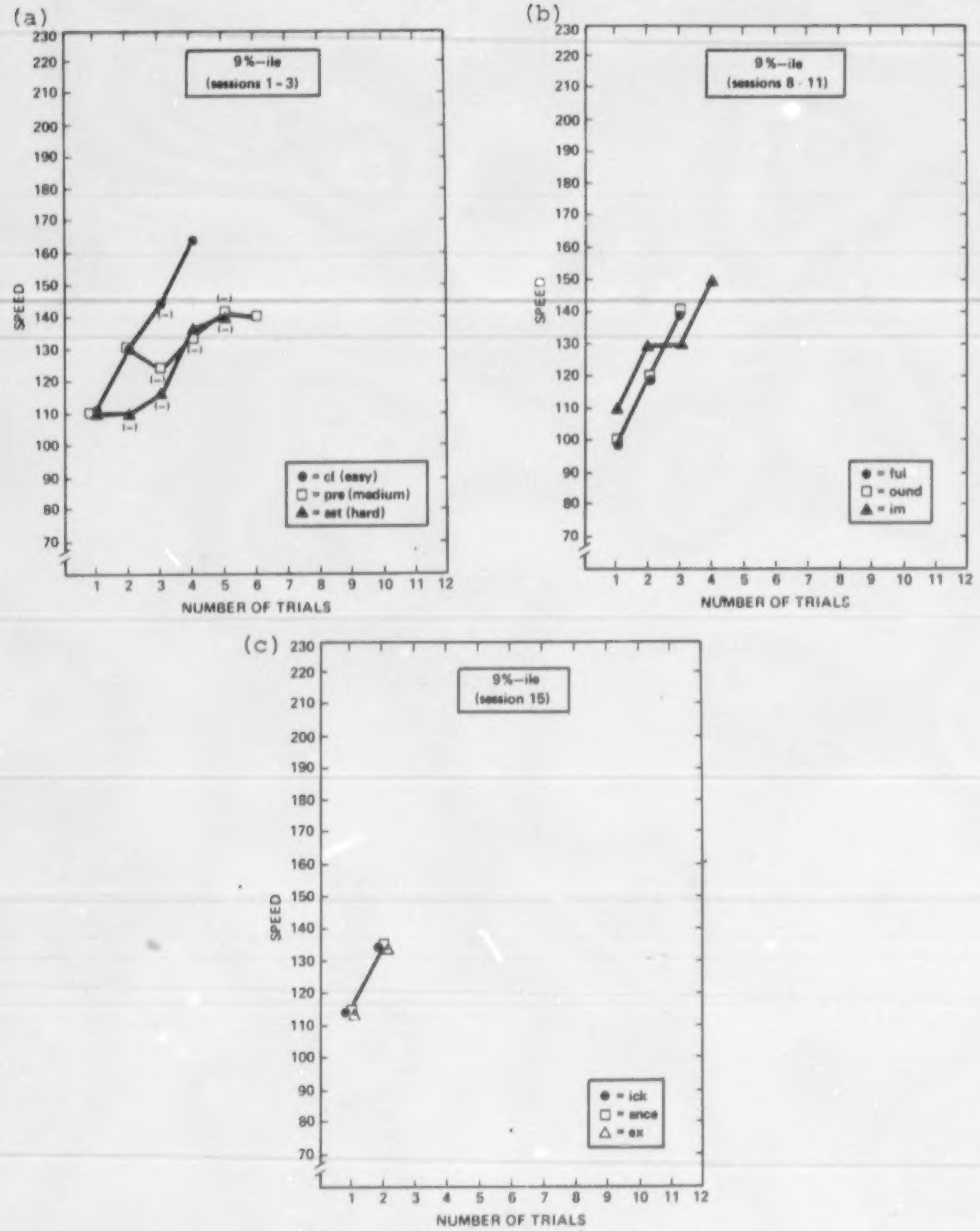


Figure 13. Performance records for Tracy on representative units at beginning (a), middle (b), and end (c) of training.

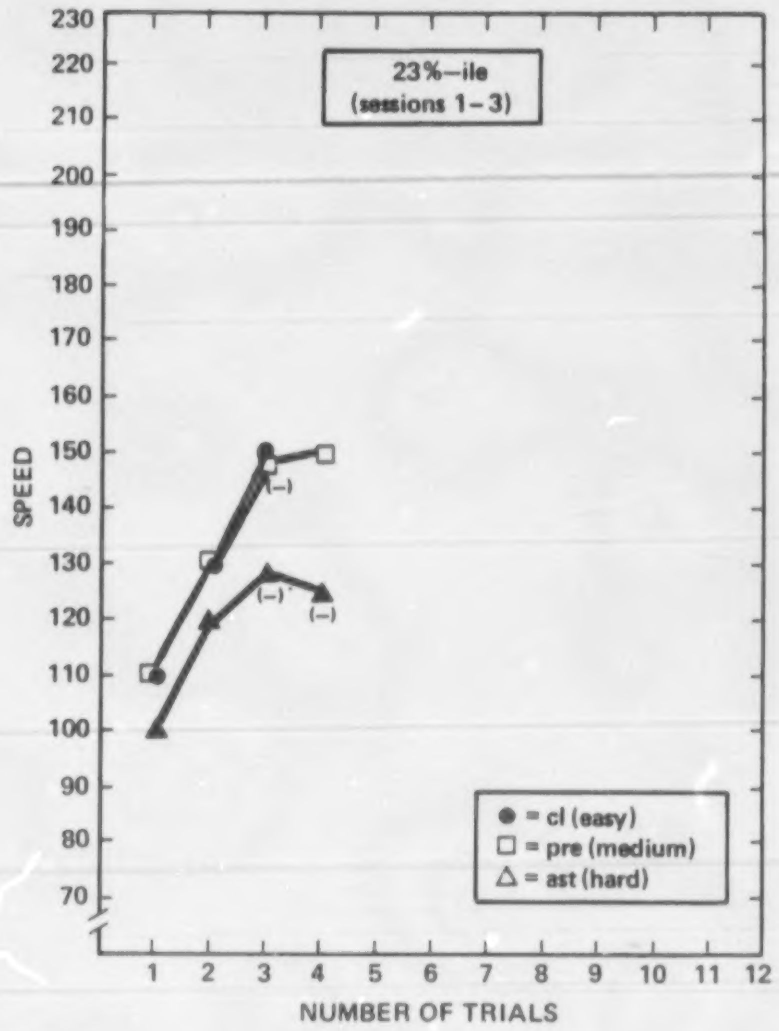


Figure 14. Performance records for Jane at beginning of training.

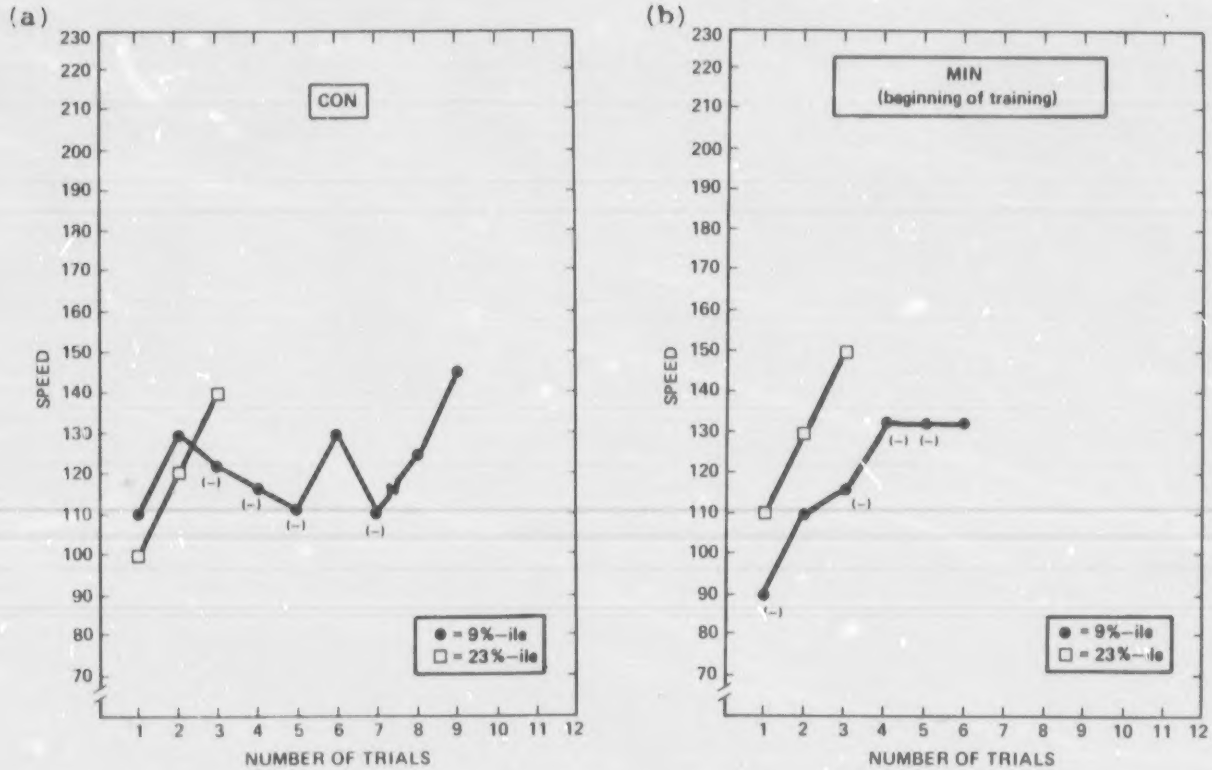


Figure 15. Reader performances for Tracy (9th percentile) and Jane (23rd percentile) compared (beginning of training).

At the beginning of training, then, Tracy and Jane offer contrasting performance profiles. They differ in number of trials to reach criterion, and in their response to unit difficulty. Tracy is less efficient overall than Jane in acquiring units. However, after acquiring units, they appear to reach comparable levels of performance.

Figures 13B and 13C illustrate Tracy's performance after two weeks and three weeks of training. Compared with her records of unit acquisition at the beginning of training, Tracy shows marked improvement in her rate of unit acquisition, although her initial performance levels are not changing appreciably. This is in contrast to Jim and Mario whose initial performance levels on new units increased as training progressed. Tracy's final performance levels are generally in the range of 145 to 150 items per minute, and this final rate is the same at all stages in training.

As Jane only completed 6 sessions (18 units) of training, comparisons of unit acquisition rates over more extended periods are not possible. For purposes of comparison, Tracy's records for the middle of training are plotted in Figure 16 along with those for Jim and Mario.

As in our discussion of Jim and Mario, we now present two tables of summary statistics that describe performance on all the units that Tracy and Jane practiced during training.

Rates of acquisition. In Tables 14 and 16, we present the number of trials to reach criterion for Tracy and Jane. As was the case with Jim and Mario, Tracy shows a clear reduction in trials to criterion over the course of the presentation of the 46 units she received. For Jane there was no reduction in the number of trials to criterion, although training covered only 18 units. The improvement in rate of learning shown by Tracy is

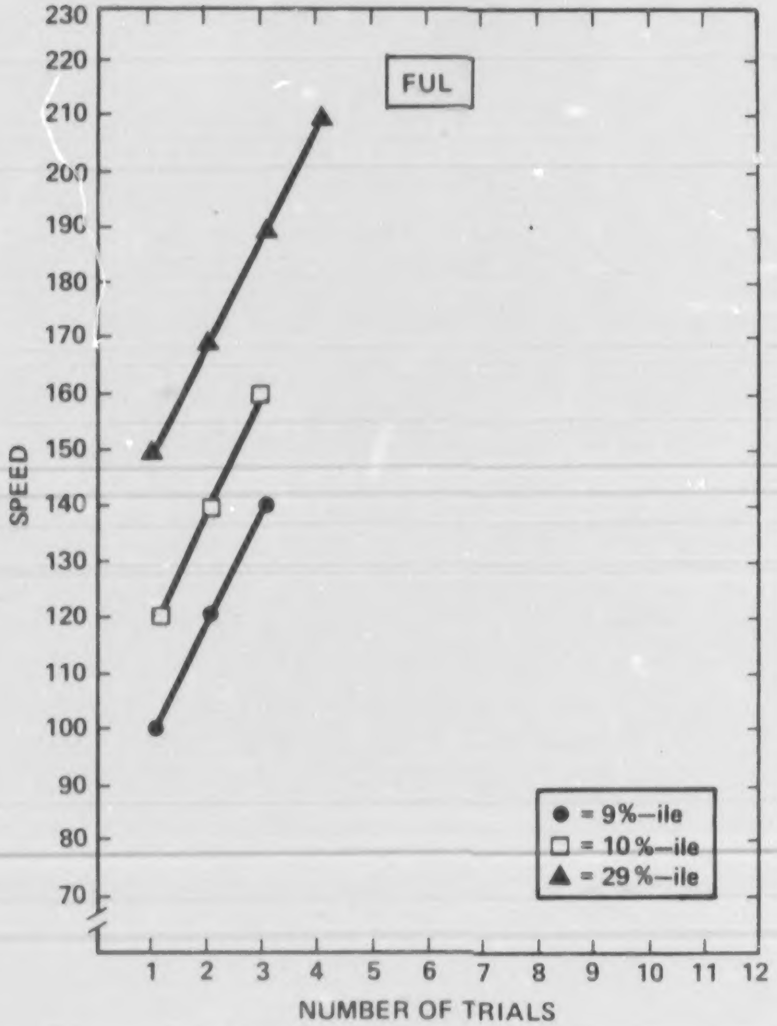


Figure 16. Tracy's performance compared with Mario and Jim at middle of training.

Table 14

(9%-ile)

UNIT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Average speed per unit	Maximum winning speed	Maint. speed
CL				→												137.0	164	
PRE							→									132.3	140	140
OUS				→												114.0	144	120
AST					→											122.4	136	126
LER						→										130.7	140	140
MIN						→										118.7	132	
POR						→										137.5	150	
ENCE					→											122.4	145	
ITE			→													130.0	150	
TR			→													130.0	150	
LY								→								128.0	153	
GEN								→								112.8	130	
TH									→							122.6	145	
CON									→							122.2	145	
VEN							→									116.1	150	
NESS							→									121.7	150	
IM								→								122.3	150	
FOR							→									118.3	150	
BIT							→									112.4	130	
ISM						→										123.7	130	
AC						→										122.0	130	
TION						→										121.3	152	
BR						→										119.3	130	
BLE			→													120.0	140	
PRO			→													118.0	140	
TY			→													120.0	140	
UN			→													120.0	140	
FUL			→													120.0	140	
OUND			→													120.0	140	
RE			→													120.0	140	
ENT				→												108.5	110	
PL				→												128.5	150	
IGHT				→												117.0	130	
DI				→												127.5	130	
CAL			→													64.0	--	
ILE						→										135.3	148	
SP						→										125.3	140	
TER						→										103.2	118	
AB						→										121.7	138	
AND				→												124.0	134	
COM				→												132.0	148	
BE					→											131.0	145	
ING					→											132.2	135	
ICK		→														125.0	135	
ANCE		→														125.0	135	
EX		→														125.0	135	

TABLE 15
(9 %-ile)
RANGE OF SPEED

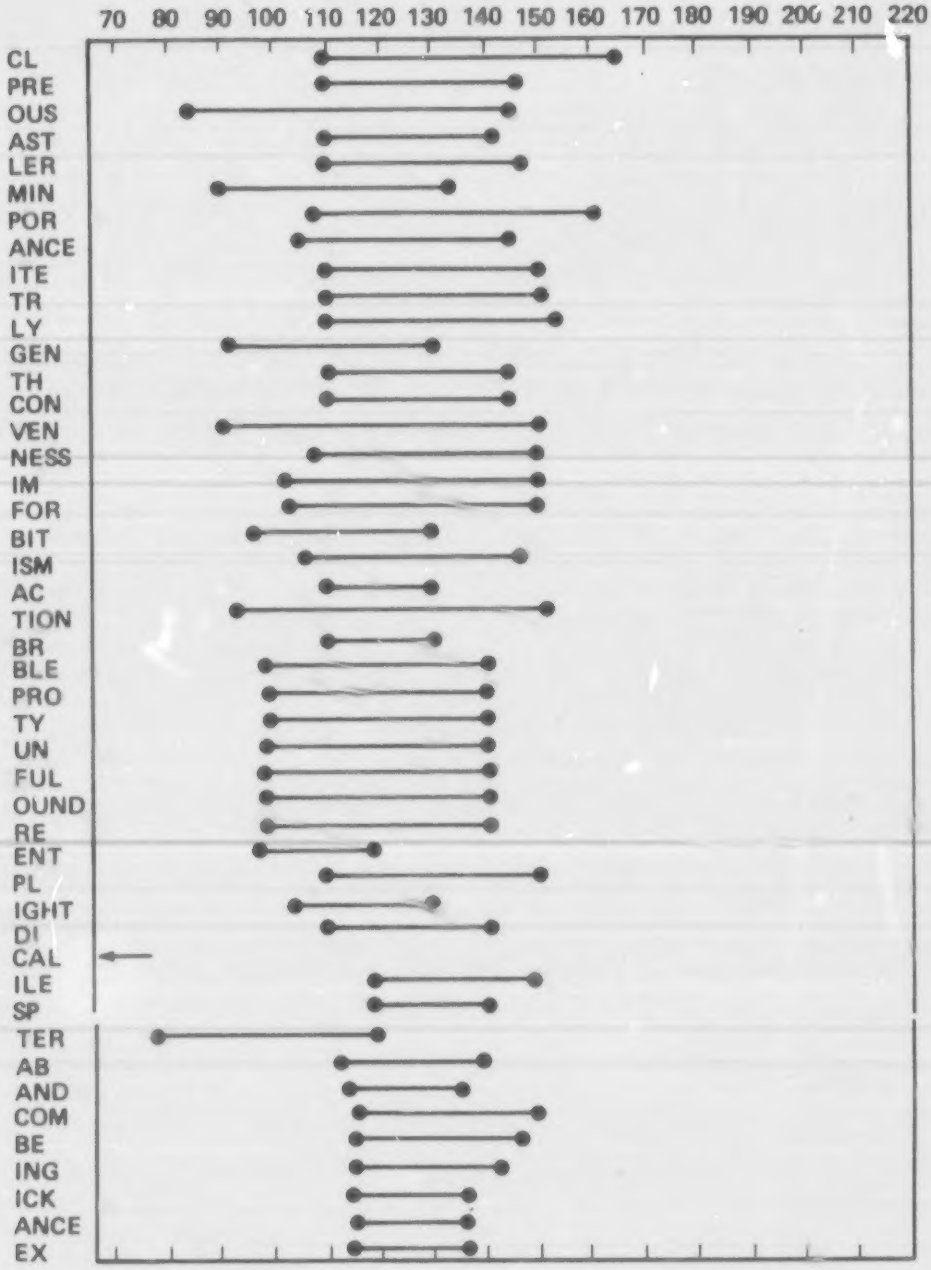


Table 16

(23%-ile)

Unit	Number of Trials 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Average speed per unit	Maximum winning speed	Maint. speed
CON	—	—	→													120.0	140	--
PRE	—	—	—	→												134.5	150	--
FOR	—	—	→													120.0	140	--
MIN	—	—	→													130.0	150	--
TH	—	—	—	→												119.5	140	--
ENCE	—	—	—	→												130.0	150	--
LY	—	—	→													120.0	140	--
CL	—	—	→													130.0	150	--
TR	—	—	—	→												130.0	160	--
AST	—	—	—	→												118.5	120	--
ITE	—	—	—	→												129.0	158	--
LER	—	—	—	→												127.0	154	--
POR	—	—	→													118.0	130	--
GEN	—	—	—	→												119.5	140	--
DI	—	—	—	→												122.8	140	--
OUS	—	—	—	→												127.8	150	--
NESS	—	—	—	—	—	→										132.7	170	--
RE	—	—	—	—	—	→										135.0	170	--

also apparent in the reduction in range illustrated in Table 15. Initially, there is great variability in initial performance levels while, at the conclusion of training, all units have consistent initial rates at 115 items per minute. Jane's training was not extended enough to permit any conclusions with respect to these trends in rates of acquisition.

Maximum performance levels. Table 15 illustrates that for Tracy there is no trend towards an increase in maximum speeds for units presented towards the end of her training sequence. Apart from the last two units presented, Jane similarly shows no gain in highest performance levels over the 18 units (Table 17). The average maximum speeds for Tracy and Jane were 140 and 148 items per minute, corresponding to detection rates of 429 and 405 msec per item in the list, respectively.

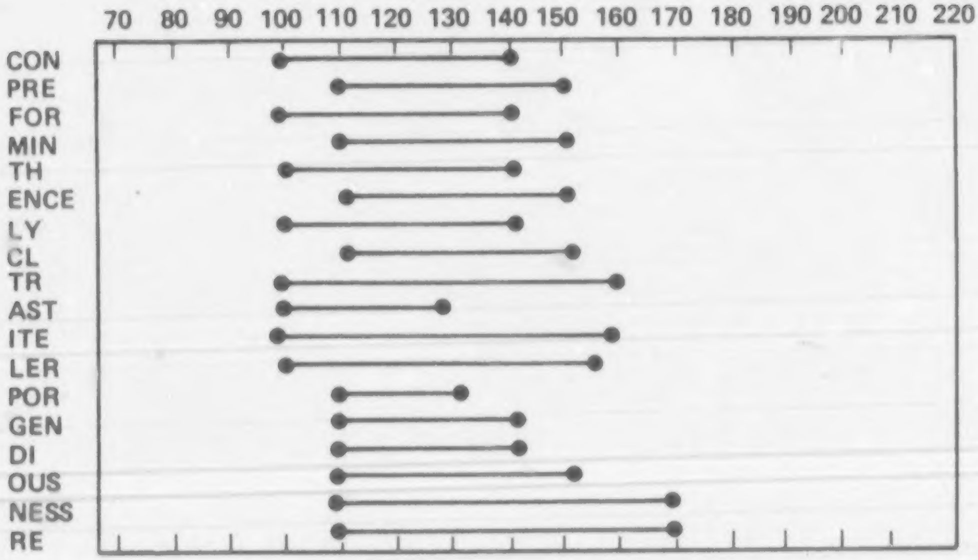
Maintenance tests. Our third statistic, average maintenance speed, describes the extent to which students maintained gains on units after a lapse of from 5-8 sessions. On Jane, we have no maintenance data. On Tracy, we have one set of four units. Her average maintenance speed on those units was 131.5 items per minute and her average highest speed on those units was 140.

Criterion Task Performance

The criterion tasks were chosen to assess the transfer of performance gains to other tasks that may implicitly involve perceptual unit identification as a component of the more complex performance. They also permit us to explore further the nature of the skill that was acquired.

1. Unit detection task (BANDWIDTH). In the unit detection task, a target unit is presented and a subject is required to detect whether or not the unit is present within a series of stimulus words, each presented for 150 msec and followed by a mask. Here individual RT for each word were recorded and

TABLE 17
(23 %-ile)
RANGE OF SPEED



performance could be evaluated for units appearing at particular locations within the stimulus word. In Figures 17, 18, and 19, the mean RTs and percentage correct detections for Jim, Mario, and Tracy are plotted for two and three-letter units, presented at the beginning of or embedded in a word. The figures are also designed to show differences in pre-training and post-training performances for units that were actually trained (60 units for Jim and Mario, 48 units for Tracy) and for a set of twenty control units that were not trained.

Analyses of variance were carried out for each subject. The factors were: Position of the target unit (at beginning or embedded within the middle of the stimulus word), Length of target unit (2 or 3 letters), Training (pretest, post test), and the Unit set (trained or untrained). These were two means for each cell, calculated from mutually exclusive sets of trials representing the particular conditions of that cell. Finally, analyses were carried out for two dependent variables: the RT for correct detections, and the percentages of correct responses.

Means for Jim are presented in Figure 17. In the analysis of RTs, there was a significant effect of Position ($F_{1,16}=31.6$, $p<.001$), and a significant Position by Training interaction ($F_{1,16}=9.4$, $p=.007$). The large effect of position in the pretest (101 msec; compared with 30 msec in the post test) suggests that Jim is initially focussing his attention primarily on the beginnings of the stimulus words. There was a significant main effect of training ($F_{1,16}=18.2$, $p<.001$) and a significant triple interaction of Training, Position, and Unit Set (trained vs. untrained units; with $F_{1,16}=7.5$, $p=.015$). Training showed its greatest effect on units appearing in mid-word positions (with a reduction in RT of 85 msec), and this effect generalized from trained (51 msec) to untrained units (120 msec), suggesting that Jim has developed an ability to more generally focus his attention across the letter of a word. Training also produced an

Unit Detection Task (Bandwidth)

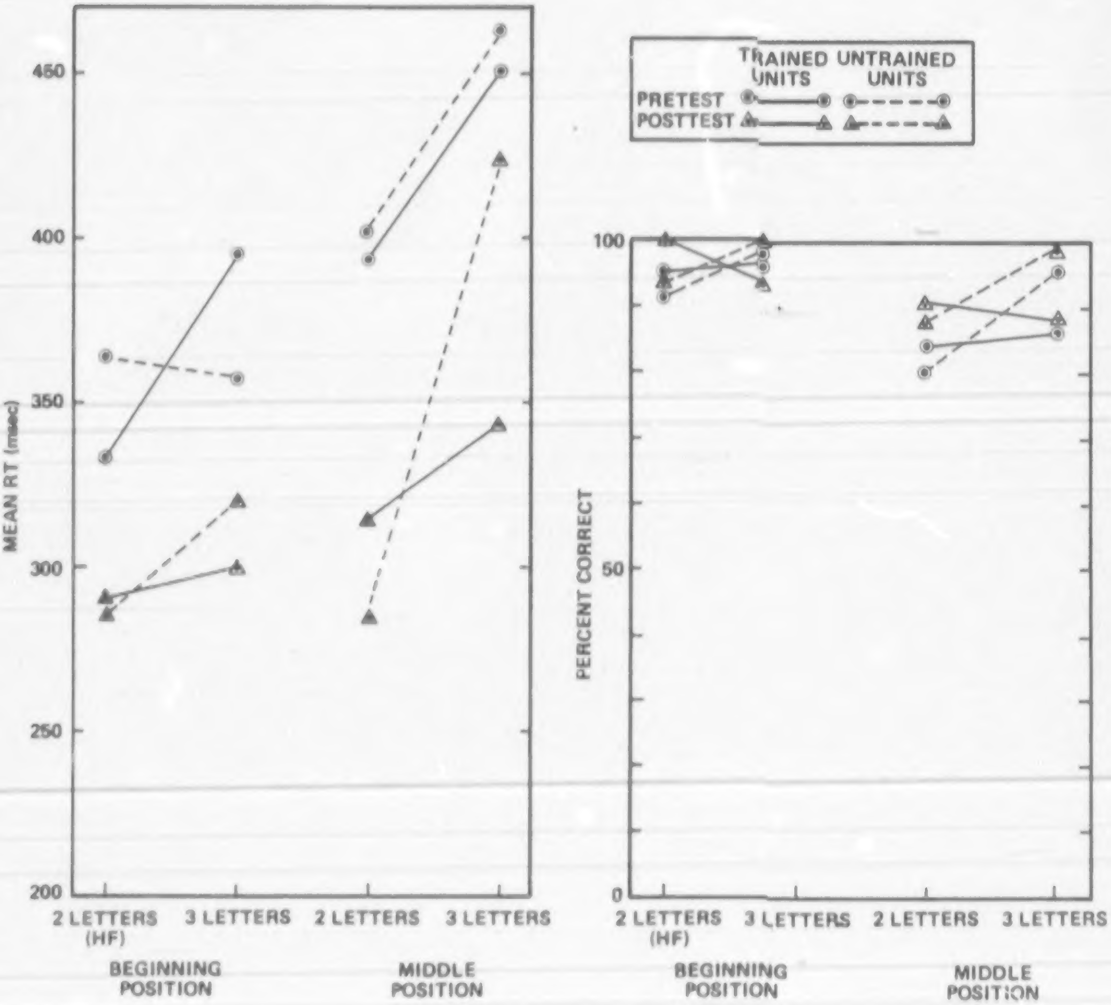


Figure 17. Jim's performance (10th percentile) on units in two positions.

Unit Detection Task (Bandwidth)

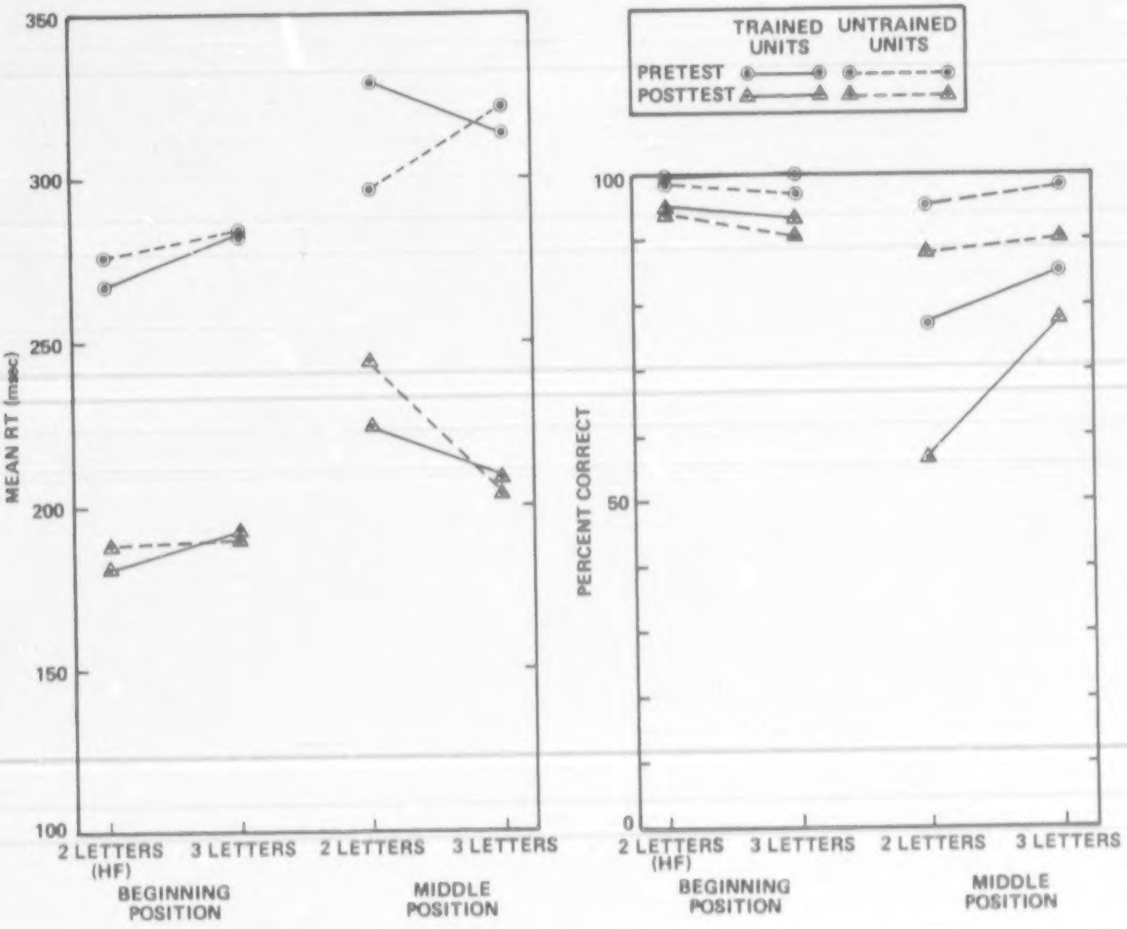


Figure 18. Mario's performance (29th percentile) on units in two positions.

Unit Detection Task (Bandwidth)

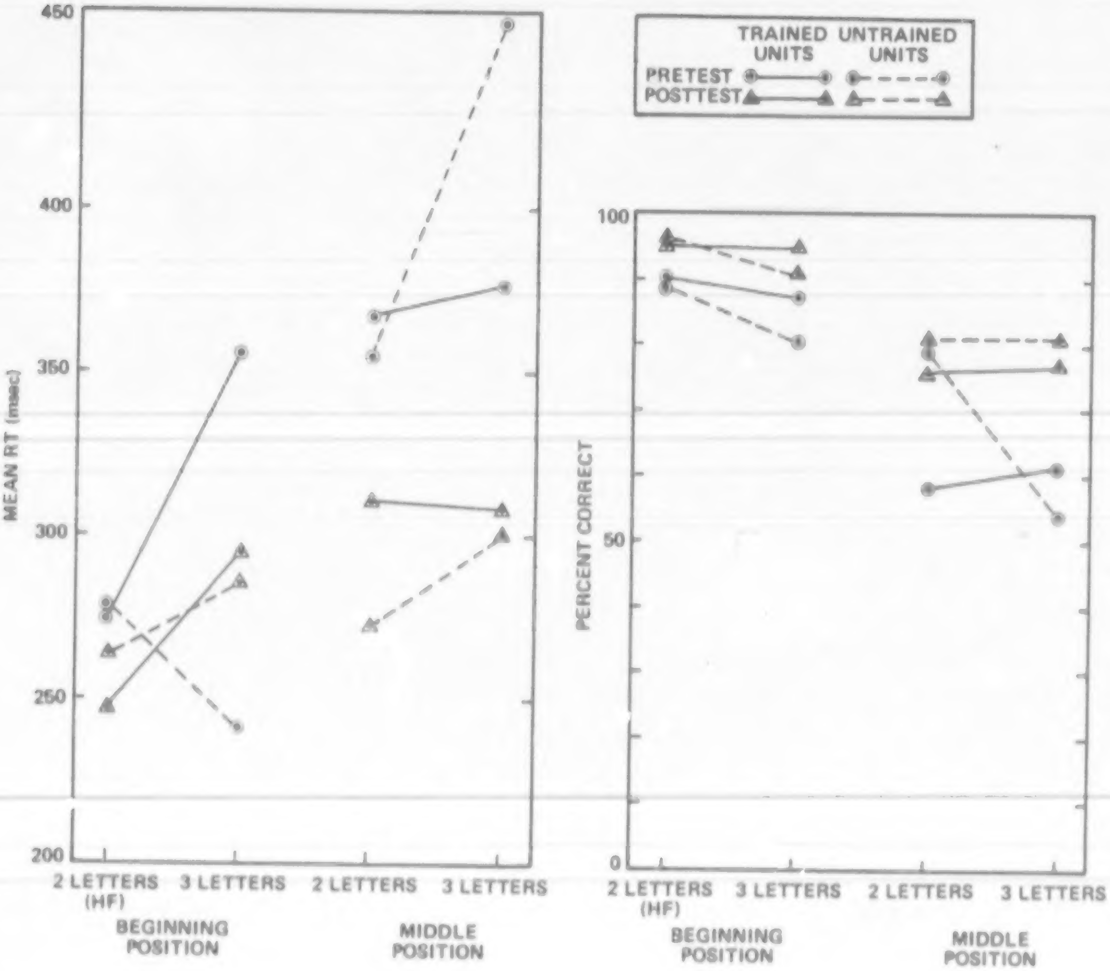


Figure 19. Tracy's performance (9th percentile) on units in two positions.

improvement for units appearing at beginnings of words (with a reduction in mean RT of 26 msec), but this effect was confined to units in the trained set (68 msec, versus -15 msec for units in the untrained set). This suggests the development of specific unit detectors for units that appear as prefixes or at the beginnings of words. Finally, there was a significant effect of unit length ($F_{1,16}$=7.1, p=.017). Jim showed greater difficulty with the long, 3-letter units, with a mean RT 31 msec longer than that for the shorter, 2-letter units. The analyses of percentages of correct responses for Jim revealed two significant main effects: First, units appearing in mid-word positions were less frequently detected (70%) than units in initial positions (91%), with $F_{1,16}$=24.9, p<.001. Second, training resulted in an increase in the percentage of correct unit detections of 12%, with $F_{1,16}$=7.7, p=.014. Thus, Jim's improvement in speed is not attributable to shifts in his detection criterion.

Means for Mario are presented in Figure 18. In the analysis of RTs there were significant main effects of Unit Position ($F_{1,16}$=45.1, p <.001) and of Training ($F_{1,16}$=302.8, p<.001). There were no other significant effects in the analysis of variance. Mean RT for units appearing in the initial position within words was 233 msec, while it was 268 msec for units embedded within the stimulus words, a 35 msec difference. The effect of training was an overall increase in the efficiency of unit detection, with a decrease in latency of 92 msec (296 msec in the pretest and 204 msec in the posttest). The effects of training were the same for trained and for untrained units (96 msec and 87 msec, respectively), and for units in beginning and medial positions (90 msec and 94 msec). One source of Mario's improvement in detection performance appears to lie in his adopting a more lax criterion for detection. Inspection of the right panel of Figure 18 will show that there was a decrease in accuracy following training. In the analysis of variance, the main effect of training was significant ($F_{1,16}$=14.0, p=.002), with an average reduction in accuracy of 8%. Accuracy was generally greater for units appearing in initial positions ($F_{1,16}$=42.6, p<.001, with an accuracy 14% greater than that for mid-word positions), and was greater for the set of untrained units than for the trained units ($F_{1,16}$=10.3, p=.005 with a difference of 7%). Finally, significant interactions of Unit Set with Position ($F_{1,16}$=18.4, p=.001) and with Unit Length ($F_{1,16}$=7.1, p=.017) support the impression gained from Figure 18 that 2-letter, and to a lesser extent 3-letter units in the medial position within words show the largest decrease in accuracy due to training. Our conclusion is that Mario has adjusted his criterion downward so as to more rapidly effect unit detections. It should be noted, however, that Mario has as a result managed to make successful unit detections 85% of the time with a mean response time of only 204 msec. This mean RT is at the bottom end of the usual RT range for detecting discrete stimuli, which extends from 230 msec to 500 msec according to Fitts (1951).

Mean detection latencies for Tracy are presented in Figure 19. In the analysis of RTs, there was a significant main effect of training ($F_{1,16}$=95.4, p<.001) that resulted in a 75 msec reduction overall in mean RT. Tracy showed a significant main effect of unit position within a stimulus word ($F_{1,16}$=47.6, p<.001, with units in initial position having an RT 53 msec shorter than units in mid-word position), and a significant interaction of position and unit length ($F_{1,16}$=9.3, p=.008, with an effect of position of 76 msec for 3-letter units, but only 30 msec for 2-letter units). Although the interaction of the position factor with the training factor was not significant, the effect of Training for units in mid-word position was 86 msec while it was 64 msec for units in the initial position, and the position effect was reduced form 64 msec in the pretest to 42 msec in the posttest. Training does not, therefore, appear to have altered Tracy's distribution of attention across the latter positions of a stimulus word to as great an extent as it did for Jim. However, there was a significant triple interaction between Unit Length, Unit Set (trained or untrained), and Training ($F_{1,16}$=9.8, p=.007). Training effects for 2-letter units (which for Tracy were significantly easier--by 43 msec--than 3-letter units; $F_{1,16}$=38.9, p<.001) were nearly the same for units in the trained and untrained sets, with decreases in RT following training of 62 msec for trained and 96 msec for untrained 2-letter units. This suggests that the improvement in performance on what for Tracy were already familiar 2-letter units is attributable to a general increase in the efficiency with which she encoded such units, regardless of whether they had been explicitly trained. The results for 3-letter units, however, were quite different. For these units, the effects of training were more confined to the units that had been explicitly trained. The effect of training was a reduction in mean RT of 102 msec for the trained 3-letter units, while it was 40 msec for the untrained units. Our interpretation is that Tracy did not have a large "vocabulary" of the longer units, and that a result of training was an increase in the number of 3-letter units available to her. Finally, we can conclude that Tracy's substantial improvement in efficiency of unit detection, from an overall mean of 395 msec in the pretest to 320 msec in the post test, was not bought at the expense of a relaxation in her criterion for detection. The analysis of her percentages of correct detection showed no significant effects. Her accuracy on the pretest was 92%, and on the posttest she made 91% correct detections.

In summary, before training, units were most difficult to detect when they were embedded in a word, and this was true for all three students. Three letter units were also more difficult to detect than two-letter units, and were more difficult to detect when they appeared within the middle of a word. Difficulty in detection was reflected in both higher RT and lower accuracy rates. Following training, students increased their efficiency in detecting units over the range of conditions. Performance discrepancies between the most difficult and least difficult conditions were reduced considerably. This is an example of what we have termed an increase in the unit bandwidth over which performance is efficient.

2. Pseudoword decoding task. Pseudoword decoding was not a skill we trained. However, perceptual unit identification may affect performance on that task due (a) to increases in the amount or accuracy of encoding orthographic information during the single 200 msec exposure of the stimulus, or (b) to possible increases in the ease of decoding from multiletter units rather than from individual letters. The latter possibility is a little more difficult to imagine happening in the absence of actual practice and utilization of large perceptual units in decoding. There were individual differences in pre- and posttest training performance on the pseudoword task and for that reason we shall discuss our three students in turn.

In the pretest (Figure 20), Jim's accuracy was only 12% at the 200 msec exposure duration. Observations of his performance showed that he typically would see only the first letter or two and on the basis of that, invent his own pseudoword. It will be recalled that the 200 msec exposure duration represents the allowed processing time prior to the onset of a visual mask. Since Jim's performance reflected a guessing strategy, he was retested on an alternate set of pseudowords at an exposure duration of 500 msec. At this duration, Jim achieved a higher accuracy level of 33.5%, ($z=4.35$, $p<.001$), but his responses were extremely slow (2.66 sec, compared with 1.36 sec at the 200 msec stimulus direction; $t_{67}=5.47$, $p<.001$). In the posttest, Jim's

Pseudoword Decoding Task

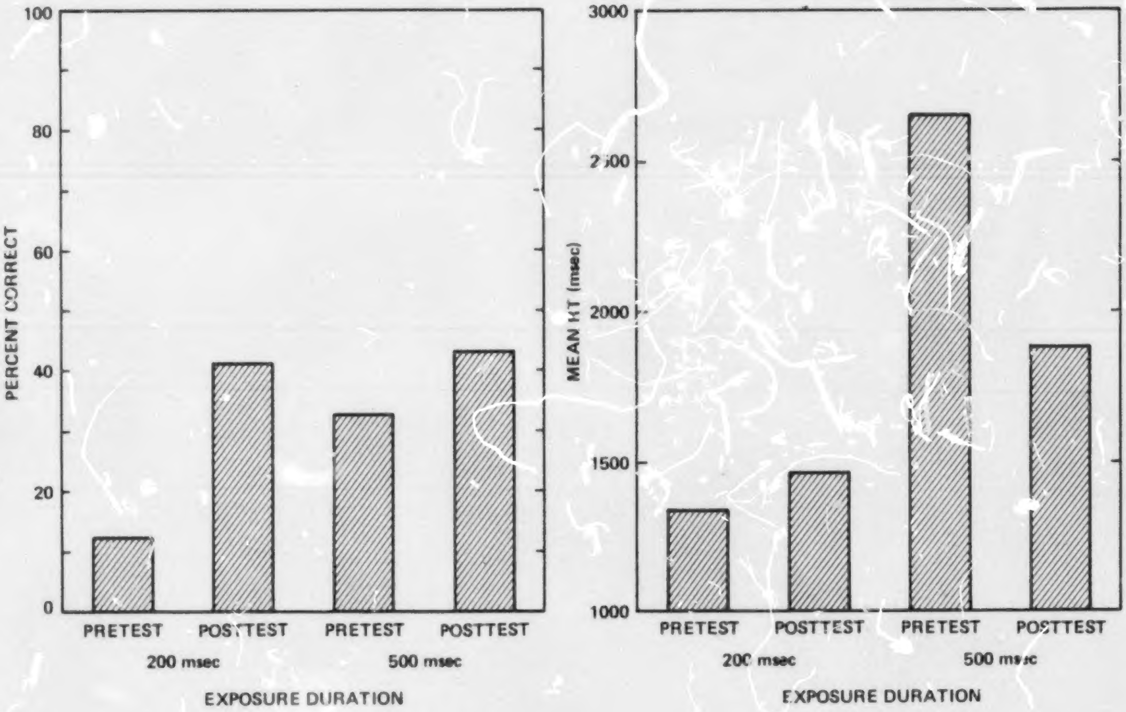


Figure 20. Effects of exposure duration on Jim's performance (10th percentile) on pseudoword decoding task.

performance level increased from 12% to 41% correct at the 200 msec exposure duration ($z=5.61$, $p<.001$) and from 33% to 43% correct at the 500 msec exposure duration ($z=1.70$, $p=.045$). There was no significant effect of exposure duration on posttest accuracy ($z=.35$, $p=.363$). His response times were 1359 msec for the pretest and 1467 msec for the posttest at the 200 msec exposure ($t_{78}=.70$, $p=.485$), and were reduced from 2659 msec in the pretest to 1885 in the posttest at the 500 msec exposure ($t_{114}=4.82$, $p<.001$). We conclude that for Jim, perceptual units training led to a more rapid encoding of orthographic information and possibly to some gains in ability to decode pseudoword items--which for him are extremely difficult.

Unlike Jim, Mario and Tracy (Figures 21 and 22) were both able to perform at reasonable non-chance levels on the pseudoword pretest at the 200 msec exposure. Mario showed an improvement in performance on the posttest from 60% correct to 76% correct after training ($z=2.99$, $p<.001$). He also showed an increase in response latency from 753 msec in the pretest to 909 sec in the posttest ($t_{192}=5.43$, $p<.001$). Tracy showed minimal gains in accuracy of pronouncing pseudowords (43% on pretest; 45% on posttest; $z=.35$, $p=.363$) and only a small increment in RT, from 948 msec in the pretest to 978 msec in the posttest ($t_{122}=.67$, $p=.25$).

Training focused specifically on the detection of perceptual units and not on the utilization of such units in the service of decoding. For this reason, we interpret the gains in performance as being due to an increase in the quantity and accuracy of orthographic information that is encoded rather than to an increase in decoding efficiency brought about by the availability of the acquired perceptual units. Developing decoding automaticity is planned as the next phase of training.

3. Span of apprehension task. Traditionally, the span of

Pseudoword Decoding Task

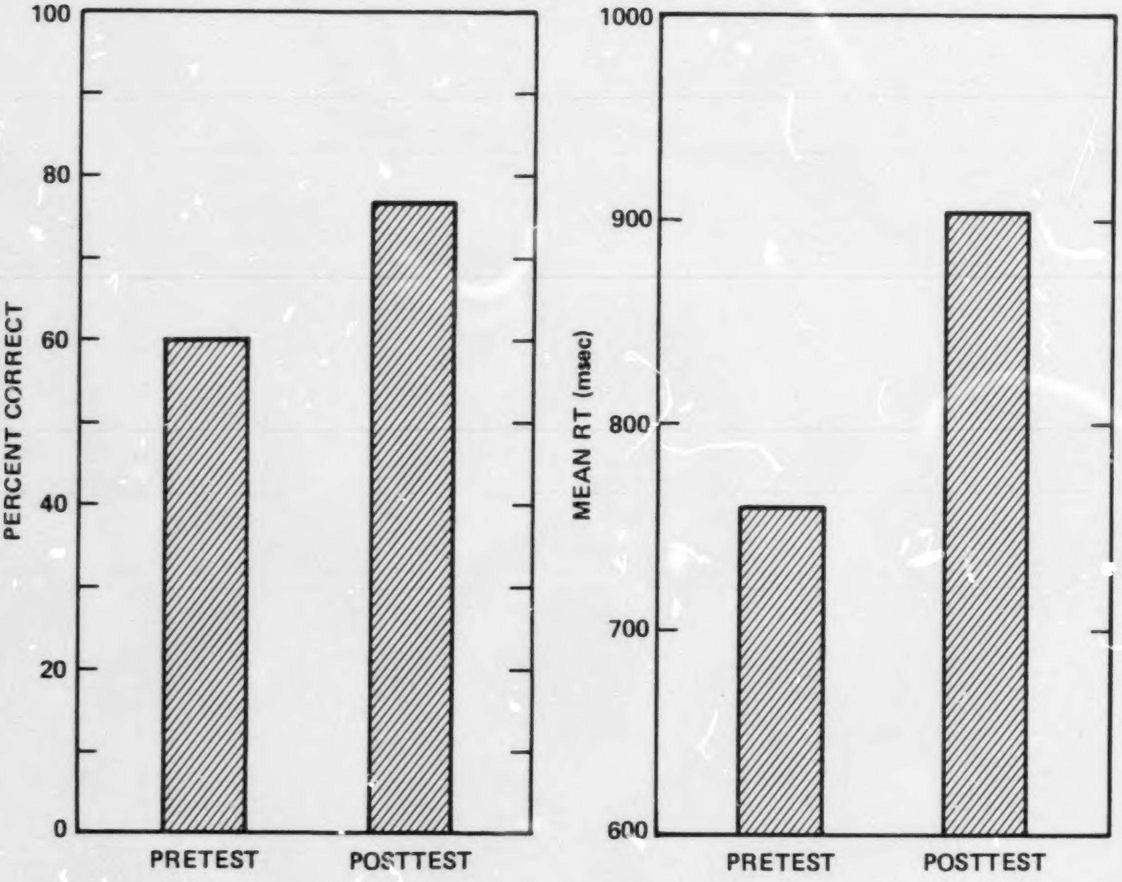


Figure 21. Effects of exposure duration on Mario's performance (29th percentile) on pseudoword decoding task.

Pseudoword Decoding Task

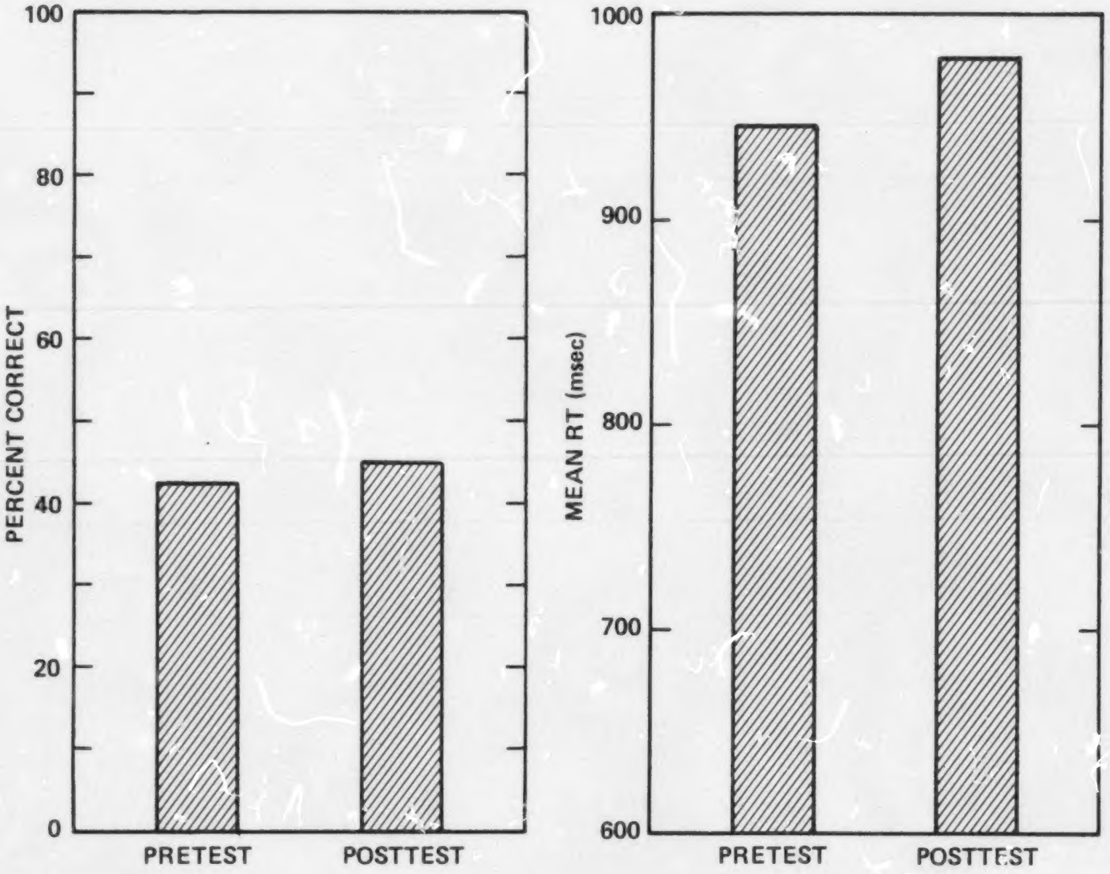


Figure 22. Effects of exposure duration on Tracy's performance (9th percentile) on pseudoword decoding task.

apprehension task was designed to measure the number of objects that could be enumerated or identified within a briefly exposed field (Whipple, 1914), or for printed materials, the number of letters or words correctly identified. Our measures of span of apprehension in reading were obtained for two conditions: with the context of a target phrase either present or absent. In the context condition essays were presented several sentences at a time, with the final few words of the last sentence at first withheld, and then--at the subject's key press--exposed for a duration (200 msec) limiting his view to a single fixation. In the no context condition, an equivalent set of target phrases were presented one after another with no meaningful context present. Pre-test and post-test results on the span of apprehension task for Jim, Mario, and Tracy are shown in Figures 23, 24, and 25.

The main purpose of the span experiment was to measure the reader's ability to employ context as a source of information useful in making lexical identifications. Prior results have shown that readers differ in this ability, measured as the increment in visual span for context as compared with baseline visual span for phrases in isolation, and our three readers differed greatly on this measure. Therefore, separate analyses of variance were carried out for each subject, with two factors, training (pretest/posttest performance) and context (absent or present).

Jim's results are shown in Figure 23. For him, there was a significant effect of training ($F_{1,156} = 7.14$, $p = .008$), and a significant interaction of training and context ($F_{1,156} = 6.94$, $p = .009$). In the pretest, Jim's span decreased from 7.85 letter spaces in the no-context condition to 5.82 in the context condition ($t_{78} = -2.15$, $p = .016$, one-tailed). Jim clearly has difficulty in simultaneously analyzing context, retaining a representation of it in memory, and identifying words within the

Span of Apprehension Task

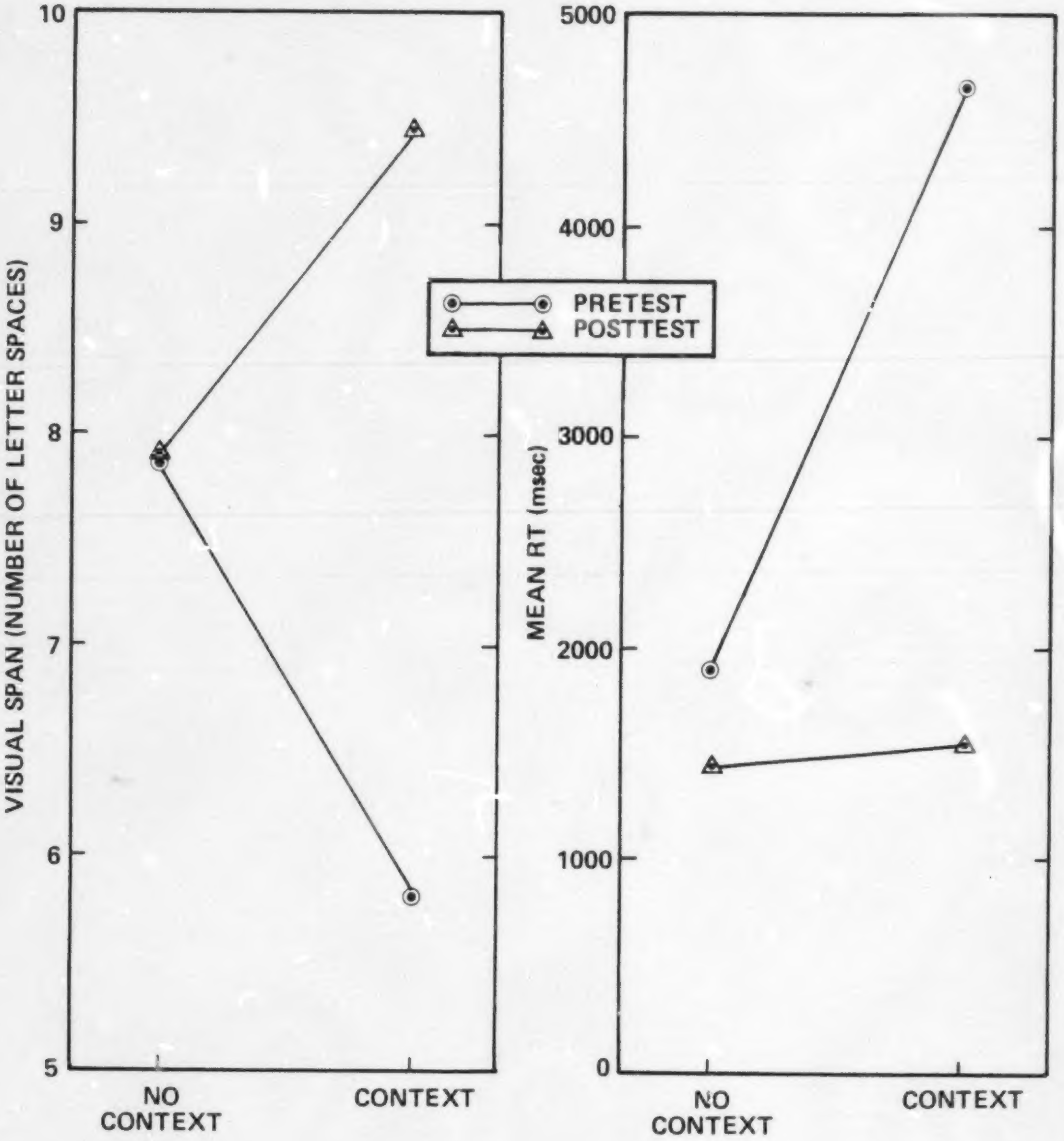


Figure 23. Jim's performance (10th percentile).

Span of Apprehension Task

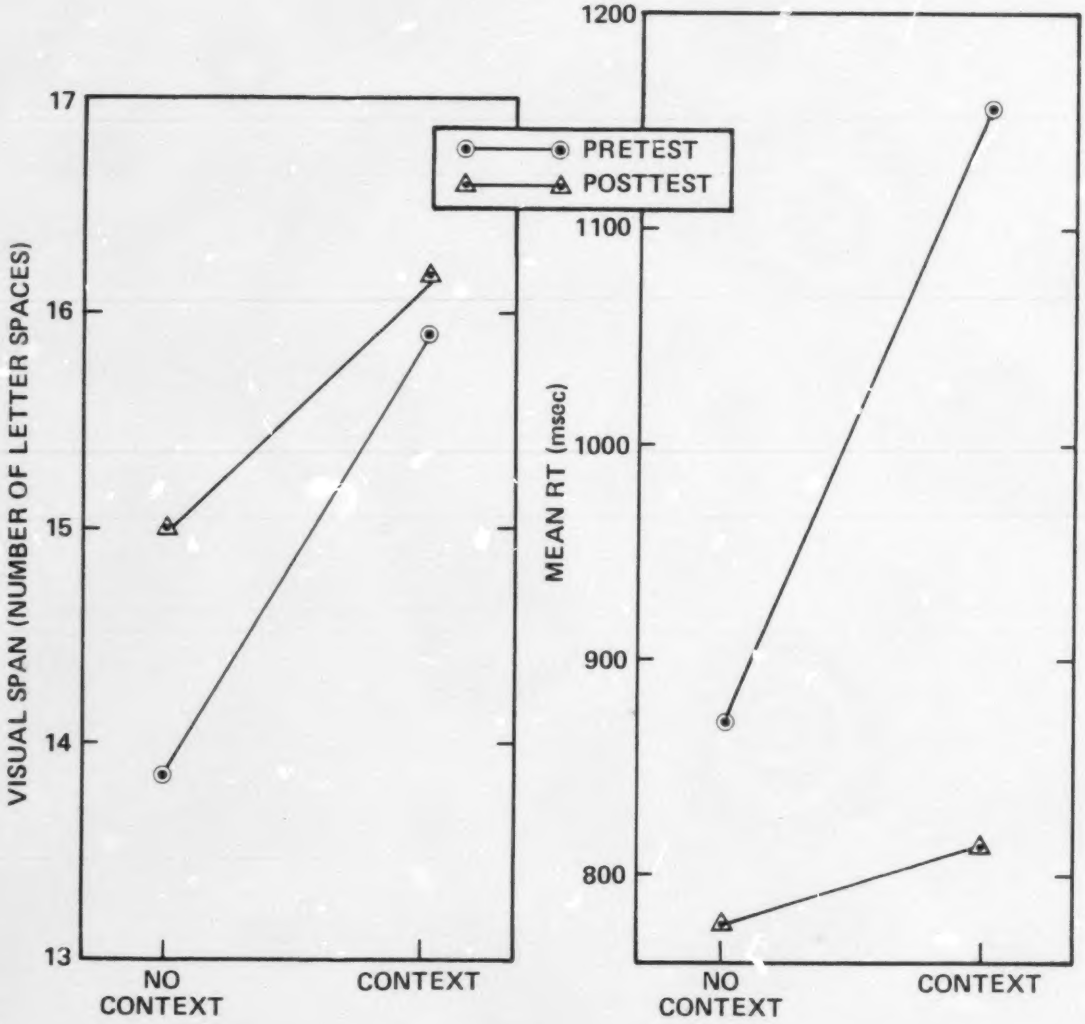


Figure 24. Mario's performance (29th percentile).

Span of Apprehension Task

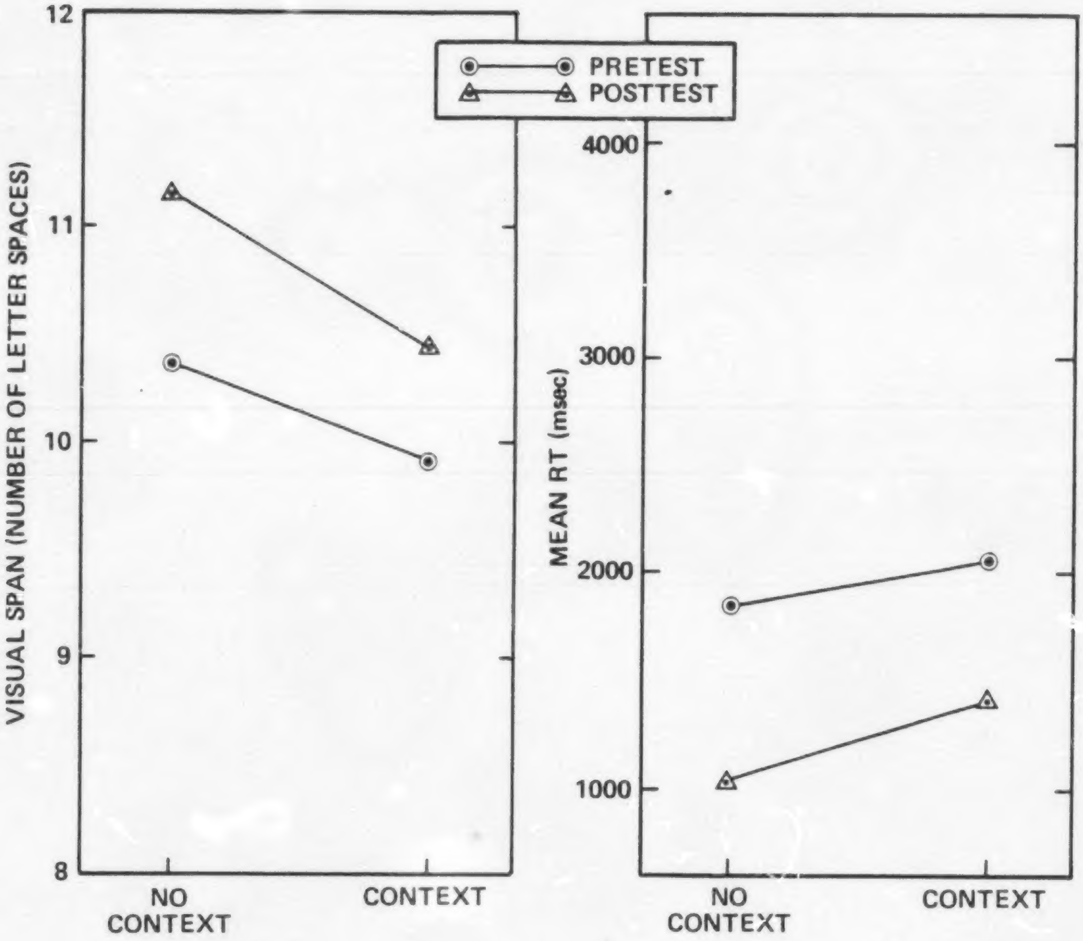


Figure 25. Tracy's performance (9th percentile).

target phrase that complete the context paragraph. Thus, his visual span is narrower in context than without context. His latency in reporting words within the target phrase is also somewhat larger in the context condition, 3816 msec, compared with 2945 msec in the no context condition ($t_{71} = 1.12$, $p = .13$). Following training, the disruptive effect of context on Jim's performance is eliminated, and he actually shows a benefit from context. His span increases from 7.88 in the absence of context to 9.45 in its presence ($t_{78} = 1.59$, $p = .055$). Thus, while training in multiletter unit identification did not increase the number of words Jim could encode in the absence of context, it appears to have decreased the attentional demands of word recognition to a high enough degree that concurrent processing of a discourse context becomes a possibility. Additional evidence supporting this conclusion is found in Jim's response latencies for reporting target phrases. When reading phrases in context, his latency dropped from 3816 msec in the pretest to 1505 msec in the posttest ($t_{69} = 3.89$, $p < .001$). When reading isolated phrases, his latencies were 2945 msec in the pretest, and 1469 msec in the posttest ($t_{75} = 2.69$, $p < .004$). Thus, the effect of training was a significant reduction in response latency, indicative of an increase in the ease or automaticity of processing in word recognition.

Visual spans obtained for Mario are shown in Figure 24. Even in the absence of context, Mario's visual span is quite large (13.9 letter spaces in the pretest). Moreover, for Mario there is a significant main effect of context ($F_{1,156} = 104.0$, $p = .018$). Before and after perceptual unit training, Mario was able to profit from context in encoding a briefly presented phrase (for the pretest, there was an increase of 2.05 letter spaces, with $t_{78} = 2.06$, $p = .02$); for the posttest, the increase was 1.18 letter spaces, with $t_{78} = 1.28$, $p = .10$). The reduction in size of context effect following training was due to an increase in Mario's baseline visual span. In the absence of context, there was an increase in span from 13.9 to 15.0 letter spaces (t_{78} = 1.43, p = .077) as a result of training. Training had no effect on visual span under the context condition (.2 letter spaces, t_{78} = .49, p = .312). Thus, perceptual units training produced an increase in the number of words Mario could encode under the perceptually more demanding, no-context condition. Under the context condition, Mario's high level of performance in the pretest reflects his ability to utilize context cues in reading. Training in perceptual unit identification does not contribute to an improvement in visual span under these conditions. However, there was a sizeable reduction in the mean response time in verbally reporting the target phrase under the context condition (964 msec in the pretest, 714 msec in the posttest, t_{76} = 1.80, p = .036), suggesting that training in unit identification may have increased the efficiency of Mario's performance in the context condition, where concurrent processing of perceptual and contextual information is required. In contrast, the reduction in response latency in the no-context condition--where concurrent processing of perceptual information and contextual information are not required--was much smaller, from 962 msec in the pretest to 888 msec in the posttest (t_{77} = .80).

Pre- and posttest results for the visual span measure are presented for Tracy in Figure 25. Tracy showed no ability to integrate contextual information with perceptual information in recognizing words or phrases--in either the pretest or posttest. She did show a small improvement in visual span as a result of perceptual units training, but these changes were not significant ($F_{1,156}$ = .78, p = .38). While her improvement in visual span was small, Tracy did show a significant reduction in response latencies of from 1825 msec to 1074 msec in the no-context condition (t_{74} = 2.80, p = .003), and from 1923 msec to 1047 msec in the context condition (t_{68} = 3.05, p = .001).

In summary, for two of our subjects there was evidence of an effect of perceptual units training on the amount of information they could encode within a single fixation, when the stimulus was a phrase excised from a text. For all three subjects, there was evidence of a decrease in the effort required reflecting an increase in the automaticity of word recognition processes. We conclude that the effects of training on the ability to utilize context are most parsimoniously interpreted as attributable to reductions in processing load attributable to word analysis, rather than as direct effects on a context utilization process.

Discussion

Nature of the Skills Acquired

The design of our training study, and in particular, the battery of criterion tasks, enabled us to determine with some specificity the nature of the skills acquired. The SPEED game was designed so that successful performance necessitated the development of perceptual skills. These could be one of several types:

1. Unit detection. Specific unit detectors could be developed for each multiletter unit trained. These detectors are postulated to have properties similar to cognitive demons in the Pandemonium System (Selfridge, 1959) which act as mini-productions, performing their function whenever defining input states are encountered (e.g., visual features). According to this view, improvements in performance should be specific to the units trained, but not be limited to the detection task.

2. Strategic application of prior orthographic knowledge. Trainees may be learning to apply strategically their prior knowledge of unit positional likelihoods to focus

their attention on specific portions of the target words in the detection task. Such a strategic skill will suffice for those conditions in which a unit--trained or untrained--appears reliably in the beginning or end of a word, but will not allow for successful performance for units whose positions are unpredictable. Such a strategy should result in successful performance on a unit detection task, but should not transfer to tasks in which units are not specified in advance as the focus of the task.

3. Shifts in criterion for detection. Trainees may develop more lenient decision criteria for detecting target units. A shift in decision criterion can result in performance improvements for detecting units that have not previously been trained as well as for trained units, but the improvements should be reflected in decreased RT accompanied by increases in the number of false unit detections and, therefore, in the number of errors. Shifts in detection criteria may have benefit in the performance of tasks other than detection tasks if, in general, the criteria of unit detectors have been modified as a result of training. For subjects who start out with high levels of accuracy, this criterion shift might result in an improvement in efficiency of unit recognition, at the expense of only small increases in rates of false detections.

4. Allocation of attention. Students may be learning to allocate attentional resources to improve efficiency of perceptual encoding, and to distribute their attention across letter positions within a target word so as to more rapidly detect units in the more difficult medial positions. Both serve to improve the quantity and

> quality of perceptual information that is encoded under perceptually demanding conditions. Such a skill would not be limited to the set of units that have been trained, nor to the detection task. Thus, it could contribute to successful performance in any task in which rapid decoding of orthographic information in a visual array is required.

The results of our training task, and more particularly, the results from our criterion tasks help us to decide among these possible alternatives.

If it were the case that students were developing only unit detectors, we would expect their performance on trained units in the detection task to be superior to that for untrained units. However, our research clearly shows comparable improvements in performance for the trained and untrained units. For example, as a result of training, Jim showed a reduction in detection latency of 47 msec for the trained units and 52 msec for the untrained units. Mario's latencies under these two conditions were 96 msec and 87 msec, and those for Tracy, 82 msec and 68 msec. Since the gains on the trained and untrained units are of similar magnitude, we conclude that an explanation based solely on the development of unit detectors is unsatisfactory. However, we have seen some evidence for the development of specific unit detectors. For Tracy, the effects of training 3-letter units were noticeably greater for trained than for untrained units. And Jim appeared to have acquired specific unit detectors for units that appear as prefixes or at the beginnings of words.

The second possibility is that subjects are learning a strategy for applying their knowledge of orthographic groupings. This leads to the prediction that successful performance on the unit detection task will be limited to units occurring in predictable positions. However, the results rule against this possibility. Performance gains as a result of training were as large or larger for the difficult units appearing in medial positions within words as they were for more regular units appearing in initial positions. The average RT gains for trained units in medial positions were 51, 104, and 94 msec respectively for Jim, Mario, and Tracy; for units in initial positions within words the corresponding RT gains were 43, 89, and 69 msec. We can also examine the variability in mean RT across units in the detection task. This statistic provides a measure of the effects of unit difficulty on each student before and after training. As unit difficulty is determined to a large extent by the predictability of a unit's position within a word, these findings provide us with another test of the same prediction. Standard deviations of mean RTs of trained units for Jim, Mario, and Tracy were 100 msec, 47 msec, and 70 msec, respectively, prior to training and were 44 msec, 19 msec, and [illegible]1 msec following training. Thus performance on difficult units in less predictable positions became less distinguishable from that for easy units in predictable positions as a result of training. The bandwidth of efficient units was effectively widened.

If students have acquired a strategy based on applying orthographic knowledge, their performance gains as a result of training should be limited to detection tasks in which a target unit is specified for each trial. However, as reported earlier, for two of our subjects there was evidence of transfer to criterion tasks involving pseudoword decoding and word recognition. In the pseudoword decoding task, significant improvement in accuracy of decoding was found for Jim and Mario--the two students who completed training. These two students, moreover, also showed gains in the number of words/letter spaces reported in the span of apprehension task. And, all three students showed significant reductions in response latencies in reporting phrases in the Span task.

There was evidence that subjects may develop more lenient detection thresholds for units, despite our efforts to control the degree of trade-off of speed for accuracy. One subject, Mario, showed an increase in errors in unit detection accompanying his marked decrease in latency. However, significant improvement in his performance on transfer tasks suggests that this shift in criterion was not restricted to the detection task and was itself beneficial.

We believe that the most compelling characterization of the skills acquired is that based upon the students' allocation of attention. The generalization of training results to untrained units and to the criterion tasks that do not explicitly involve unit detection supports this view. Moreover, the close identity in performance levels on the unit detection task for the trained and untrained units is a mark of the power of the attentional component in ensuring efficient performance in the unit detection task. There was also evidence of change in the distribution of attention. For Jim, who was least able to report units in medial positions, training brought an improvement in his distribution of attention across a visual array. The attentional skills acquired are clearly more general than the development of a specific unit vocabulary and are applicable in tasks other than the detection task.

Our results provide strong support for the interactive theory of reading, particularly the notion of rate limiting processes (Perfetti & Roth, 1981). According to these authors, a process is rate limiting to the extent that other processes depend upon its output. Our training has, even without the inclusion of practice in word decoding or word recognition, succeeded in improving those skills. In this example, the improvement in word recognition is due to the increase in efficiency and quality of orthographic information encoded within a single fixation. We have also found evidence for improvement in criterion task performance based upon a decrease in competition for shared resources. Before training one of our low ability readers, Jim, showed an interference between two processes that are not data linked, but presumably resource-linked. His performance in rapidly identifying words within a single fixation (target phrase) was significantly impaired when an additional source of information--contextual information--was supplied. The occurrence of this interference effect allowed us an opportunity to assess the effects of training--which had a demonstrable effect on word decoding--on the amount of interference due to this competition for processing resources. Not only was all interference in the context task eliminated, but following training there was a significant benefit of a prior context on visual span.

From training one subcomponent, perceptual unit identification, we have seen transfer that is attributable to process interactions that we have classified as data-linked and resource-linked. These incidences of transfer parallel the theoretical links between perceptual decoding and comprehension processes discussed in our earlier analyses of covariance structures (Frederiksen, 1981). Improvements in decoding automaticity may thus have a beneficial effect on discourse comprehension. The next phase of training will focus on developing decoding automaticity and on the evaluation of this possibility.

Nature of the Instructional Design

We view our instructional system as being composed of three major design components: the logic of the instructional task, the mode of training, and the delivery of instruction. We discuss these in turn.

Logic of the instructional task. The cognitive theory of reading specified the skills to be trained, the order of training specific subskills, features of the training environment, and the criteria for successful performance. The key unifying concept was the negative effect of nonautomatic performance on processes that must operate concurrently in reading. Thus, the finding of a general negative transfer of nonautomatic, effortful decoding to other reading components coupled with the clear deficiency in decoding performance shown by poor high school readers led us to select word analysis skills as the focus of our instruction. The additional finding that good and poor readers differ in the perceptual units employed in decoding led us to begin with the perceptual component. The training task was designed to meet several requirements derived from the cognitive theory. It allowed us to train a subcomponent in isolation in a manner such that the criteria for performance required the development of the designated perceptual skill, and permitted continuous feedback as to efficiency and accuracy of performance. This procedure, while unorthodox in reading practice, has been recognized as an effective and beneficial procedure in the literature on training perceptual motor skills (cf. Bilodeau, 1966). Finally the cognitive theory enabled us to hypothesize those skill areas that should exhibit transfer of training and thus to a specification of the criterion reading measures to be included in the study.

The results of our training study have clearly demonstrated that extremely low ability readers of high school age can acquire fundamental perceptual skills over a training period as brief as four to six weeks, forty minutes per day. The improvement in perceptual skills persisted when units were retested and generalized to tasks that implicitly invoked them but did not explicitly require them for successful performance. We have seen improvement in the ability to decode pseudowords under difficult masking conditions and in the ability to incorporate orthographic information along with information from context in encoding words within a phrase exposed tachistoscopically. We feel that the perceptual and attentional skills acquired will form a basis for improvement when our readers are subsequently trained in decoding and use of context.

The mode of training. It is part of the lore of educational practice that for students to learn a skill, in particular an inherently dull one, practice on it must be engaging. Games are notable for their motivational appeal. For these reasons, we implemented perceptual units training--a good example of a fundamentally uninspiring skill--in a microcomputer-based game that succeeded in engaging students in practice.

The appeal and power of the game SPEED derive from the specificity[1] with which it defines the player's goal and informs him of his progress. Specificity is achieved by means of the speedometer and error lights which interact to define the conditions of the game and the levels of challenge to be met by the player. The goal of SPEED is for the player to accelerate his rate of unit detection without sacrificing accuracy. In this way, the game simulates the sort of speed-accuracy bind in which the skilled reader finds himself. Thus, increased speed cannot be bought at the expense of extreme inaccuracy. Rather, students can maximally increase the challenge of the game by finding the optimal interplay of speed and accuracy. The delivery of direct, continuous, and highly informative feedback through the speedometer and error lights enables the player to discover this optimal interplay.

In summary, the gaming environment of SPEED was designed to provide practice that is at once engaging and informative. It derives additional instructional power from the fact that skill in winning the game is isomorphic to skill in detecting perceptual units. SPEED therefore represents our approach to the problem of designing intrinsically motivating instructional environments (cf. Malone, 1980), an approach that we will extend to the design of gaming environments for training in decoding and use of context.

The delivery of instruction. The plan for instruction included the specification of a set of principles and procedures for carrying out perceptual units training. These principles and procedures focused on five factors: the selection and grouping of units for training, their sequence, the frequency and intensity of practice, the determination of performance criteria, and the maintenance of criterion-level performance. The set of instructional principles and procedures were constructed to encourage the development of efficiency and accuracy in performance over a broad band of perceptual units and to ensure appropriate levels of challenge for the students. For example, automaticity of performance, as the goal of training, required that we determine in a very precise way the optimal conditions for practice. We accomplished this by carefully observing patterns of student performance and adopting those conditions that were most effective. Similarly, to promote efficient performance over a broad band of units we alternated practice on units that varied with respect to their positional likelihood and frequency. As these factors were closely related to a unit's difficulty, this alternation ensured that students would experience success as well as challenge.

In order to assess learning during training, we included checks on the maintenance of criterion-level performance. These also provided us with built-in tests of the effectiveness of our training principles and procedures.

We have been able to prescribe a set of instructional principles and procedures designed to foster the acquisition of skill in perceptual parsing. These principles and procedures are consistent with some of the general laws of learning concerning, for example, motivation and the nature of practice, and take account of individual differences as well, for example, in rates of acquisition and levels of speed attained. At the same time, they distill the essential features of skillful performance in this domain and reflect the specificity that characterizes the entire instructional system we have been describing.

We are confident that the structure we have developed for delivering instruction will serve as a very useful framework for the specification of principles and procedures for carrying out instruction in other skill components. Our confidence stems from three sources. First, the objectives of training which informed this structure appear to be uniform across skill components. Second, the principles and procedures were subject to empirical tests during the course of training. Finally, while we had a strong interest in addressing individual differences in performance, we were able to develop principles and procedures that worked effectively for each of the students we trained and that should have general applicability for other trainees. In our future work, we plan to train additional students using the SPEED game, and to continue to evaluate the effectiveness of our training principles. Further, we shall examine transfer of training in SPEED to the acquisition of additional reading components, using instructional games currently under development.

Footnotes

[1] Indeed, one of our trainees compared the Bandwidth task (unit detection in a non-gaming environment) with SPEED by commenting that the former "lacked definition."

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Appendix A

Suffix Group			Prefix Group		Vowel/Consonant Group		
CIOUS	S	5	WITH	4	AUGH	V	4
TIOUS	S	5	PARA	4	CIAL	C	4
ANCE	S	4	FORE	4	CRED	C	4
AYED	S	4	HOMO	4	EASE	V	4
CIAL	S	4	POLY	4	EIGH	V	4
CIDE	S	4	BENE	4	IGHT	V	4
CIST	S	4	ANTI	4	IOUS	V	4
DENT	S	4	HYPO	4	OUGH	V	4
EASE	S	4	MONO	4	OUND	V	4
EIGN	S	4	CATA	4	TION	C	4
ENCE	S	4	SEMI	4	ACK	V	3
ENSE	S	4	QUAD	4	ECK	V	3
ENGE	S	4	POST	4	ICK	V	3
INCE	S	4	KILO	4	OCK	V	3
GRAM	S	4	PROS	4	UCK	V	3
LESS	S	4	ENDO	4	ORD	V	3
MENT	S	4	MESO	4	ATE	V	3
NESS	S	4	ENTO	4	IVE	V	3
OUGH	S	4	COM	3	OUD	V	3
SION	S	4	CON	3	OUS	V	3
SIVE	S	4	PER	3	ISH	V	3
TIAL	S	4	DIS	3	USH	V	3
TICE	S	4	PRE	3	AB	V	2
TIES	S	4	PRO	3	AC	V	2
TION	S	4	OUT	3	AD	V	2
TIVE	S	4	FOR	3	AF	V	2
TURE	S	4	COL	3	AG	V	2
PORT	S	4	SYL	3	AL	V	2
AGE	S	3	TRI	3	AM	V	2
ALE	S	3	DIA	3	AN	V	2
AND	S	3	MIS	3	AP	V	2
ATE	S	3	UNI	3	AR	V	2
BLE	S	3	MID	3	AS	V	2
CAL	S	3	NON	3	AT	V	2
CLE	S	3	PAN	3	AV	V	2
DLE	S	3	SYM	3	AW	V	2
GLE	S	3	SYN	3	ED	V	2
ELE	S	3	OFF	3	EL	V	2
FLE	S	3	HEX	3	EM	V	2
PLE	S	3	DYS	3	EN	V	2
TLE	S	3	IN	2	ER	V	2
ACE	S	3	BE	2	ES	V	2
AKE	S	3	EX	2	ET	V	2
IKE	S	3	RE	2	EV	V	2
ILE	S	3	UN	2	EW	V	2

Appendix A (cont,)

ISM	S	3
IED	S	3
IES	S	3
FUL	S	3
ING	S	3
IST	S	3
IZE	S	3
PER	S	3
TER	S	3
GER	S	3
DER	S	3
VER	S	3
TRY	S	3
ED	S	2
ER	S	2
LY	S	2
TY	S	2
DE		2
AC		2
IM		2
OB		2
AD		2
AN		2
EM		2
AS		2
EF		2
AF		2
AB		2
EC		2
AM		2
BI		2
CO		2
IR		2
AG		2
DU		2
IL		2
ON		2
BY		2
ID	V	2
IF	V	2
IG	V	2
IL	V	2
IM	V	2
IN	V	2
IR	V	2
IP	V	2
IS	V	2
IT	V	2
OB	V	2
OD	V	2
OG	V	2
OF	V	2
OL	V	2
OM	V	2
ON	V	2
OP	V	2
OR	V	2
OT	V	2
OW	V	2
AI	V	2
AU	V	2
AY	V	2
IE	V	2
EA	V	2
EE	V	2
EI	V	2
EU	V	2
EY	V	2
OA	V	2
OI	V	2
OO	V	2
OU	V	2
OY	V	2
BR	C	2
CL	C	2
DR	C	2
FL	C	2
GR	C	2
PL	C	2
PR	C	2
SP	C	2
TR	C	2
SH	C	2
PH	C	2
WH	C	2
TH	C	2
CH	C	2
QU	C	2
CK	C	2

Appendix B

Unit: cl		Unit: gen	
Test Word	Filler Word	Test Word	Filler Word
1. claimed	chaired	1. generality	gynecology
2. clanged	freeway	2. generating	treasonous
3. clarion	chalice	3. generation	goniometer
4. classed	grenade	4. generators	grenadiers
5. clauses	slavish	5. generosity	redundance
6. cleanly	predate	6. generously	transplant
7. cleanup	slaver	7. generic	gnostic
8. cloture	diapers	8. genesis	probity
9. clamping	clovenly	9. genetic	gnocchi
10. classics	freehold	10. genteel	squalid
11. clearest	slattern	11. genuine	germane
12. clemency	frequent	12. detergency	wholesaler
13. climaxes	alembic	13. indulgence	outrageous
14. clinical	prejudge	14. insurgency	surpassing
15. clocking	slipknot	15. negligence	pentethion
16. closed	presto	16. pathogenic	orthogonal
17. closet	elicit	17. geneology	resultant
18. clouds	trepan	18. genocidal	geologize
19. clover	eleven	19. gentility	character
20. clucks	prefix	20. genuinely	gerundive
21. clumsy	slalon	21. generally	invisible
22. cloak	greed	22. generals	geminate
23. claws	slams	23. generous	pellagra
24. clasp	green	24. genitive	ganister
25. click	slack	25. genotype	gnathite
26. cliff.	wrest	26. collagen	plethora
27. clamorous	elsewhere	27. divergent	packaging
28. clarifies	presidium	28. negligent	intrigant
29. clattered	challenge	29. resurgent	obstinacy
30. clientele	prejudice	30. gender	geisha
31. clippings	sluggishly	31. genial	gnawed
32. acclimate	treasurer	32. gentry	ponder
33. declaring	foolhardy	33. generically	reincarnate
34. inclusive	frequency	34. gentlemanly	gelatinized
35. reclining	yielding	35. eugenic	mercury
36. cyclist	kindred	36. regency	lexical
37. enclave	evelong	37. emergent	integers
38. enclose	lamprey	38. ontogeny	micawber
39. unclean	gosling	39. legendary	pageantry
40. declared	entirety	40. pungent	longing
41. exclaims	mealtime	41. exigency	quotient
42. included	fortress	42. endogenous	caliginous
43. unclench	choleric	43. octogenarian	hallucinated
44. clarifying	figurehead	44. heterogeneity	permanganate
45. classifies	albuminous	45. interagency	spherometer
46. clodhopper	discretion	46. generatively	octosyllable
47. clad	elan	47. regenerate	manzanella
48. clef	urea	48. tangential	loggerhead
49. exclusions	amsliorate	49. cryogenic	inorganic
50. unclasping	discrepant	50. ontogenesis	sympetalous

Appendix C

SPEED TRAINING: Session #7 Subject: Jim (10%-ile)
Date: 2/19/81

Unit	Max Speed[1]	# of Words[2]	Goal Speed[3]
GEN	110	-29	140
ENCE	105	-16	137
AST	77	-10	121
LY	135	-57	149
MIN	108	-44	112
GEN	92	-17	130
ENCE	110	0	125
AST	65	-62	97
LY	129	-71	155
MIN	102	-35	128

SPEED TRAINING: Session #3 Subject: Jane (23%-ile)
Date: 5/27/81

TR	140	25	140
AST	128	-32	140
ITE	138	-45	140
LER	134	-37	140
NESS	110	29	110
RE	110	37	110
NESS	130	29	130
RE	130	35	130
TR	160	47	160
AST	126	-79	148
ITE	158	27	158
LER	154	69	154

Appendix C (cont.)

The above comparison of records of training for Jim (10%-ile) and Jane (23%-ile) illustrates the application of the principle to defer second trials on a set of units if the first trials resulted in crashes. The development of this principle was motivated by performance patterns such as the one illustrated at the top for Jim.

[1] Max Speed: refers to the highest speed achieved in the trial at the moment the student wins or crashes. In the case of a win it is the goal speed.

[2] # of Words: refers to the number of words from the inspection list that a student sees before winning or crashing. A win is indicated when:

(a) max speed = goal speed
(b) # of words doesn't have a negative sign

[3] Goal Speed: refers to the speed that is the goal for that trial. It is preset by the computer based on the previous performance on that unit.

Appendix D

SPEED TRAINING: Session #6 Subject: Jim (10%-ile)
Date: 2/18/81

Unit	Max Speed	# of Words	Goal Speed
PRE	136	-35	170
PRE	132	-18	156
PRE	134	-45	152
PRE	136	-25	154
PRE	124	-24	156

SPEED TRAINING: Session #8 Subject: Jim (10%-ile)
Date: 2/23/81

TH	140	61	140
TH	150	-47	160

SPEED TRAINING: Session #10 Subject: Jim (10%-ile)
Date: 2/25/81

AST	105	45	105
AST	125	35	125

The above records of training for Jim (10%-ile) provide a comparison of the effects of virtually unlimited massed practice trials (*pre*) and massed practice that is limited to two consecutive trials (*th* and *ast*). As trials on *pre* accumulate, Jim makes no progress at all (never exceeding 136) and falls off on the last trials to 124. On the second trial for *th*, Jim improves by 10 units of speed (140 to 150) over the first trial, although he falls short of his goal speed (160). On *ast*, he not only reached the goal speed set for the second trial (125), but he does so with greater accuracy than on the first trial (35 words to reach 125 as compared with 45 words to reach 105).